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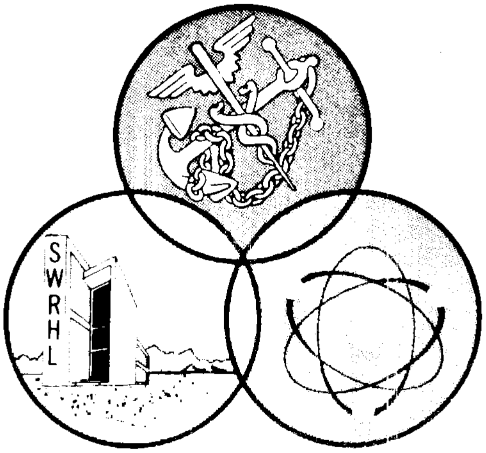

PROCEEDINGS

for the

SYMPOSIUM

on

PUBLIC HEALTH ASPECTS OF PEACEFUL USES OF NUCLEAR EXPLOSIVES

sponsored by

the

SOUTHWESTERN RADIOLOGICAL HEALTH LABORATORY

Bureau of Radiological Health

Las Vegas, Nevada

April 7 through 11, 1969

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FOREWORD

The Southwestern Radiological Health Laboratory is very pleased to have sponsored this Symposium on the Public Health Aspects of the Peaceful Uses of Nuclear Explosives. The primary purpose of the Symposium was to disseminate and document current information and data on the public health aspects of this promising new technical field.

In addition, it served to identify potential problem areas, stimulated discussion, and provided an opportunity for exchange of ideas and rapport between and among various individuals and groups sharing interests in various facets of Plowshare technology.

These proceedings should serve these objectives and provide a resource of relevant information which may be used to evaluate what is presently known and unknown in the public health and safety area of the technology for peaceful applications of nuclear explosives.

Dr. Melvin W. Carter
Southwestern Radiological Health Laboratory

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Chairman: Dr. Melvin W. Carter
Director, SWRHL
U. S. Public Health Service
Las Vegas

PUBLIC HEALTH AND PLOWSHARE

James G. Terrill, Jr.
Consumer Protection and Environmental Health Service
U. S. Public Health Service
Washington, D. C.

ABSTRACT

The protection of public health and safety is a principal area of concern in any application of nuclear energy. A health and safety analysis must be conducted and reviewed by appropriate agencies and the final results made available to interested agencies and groups, both public and private, prior to the application. This is especially important for the Plowshare Program - the peaceful uses of nuclear explosives - where the public is to be the ultimate beneficiary.

Because public health must be a primary concern in the Plowshare Program, it is essential that the potential risks be weighed against the expected benefits to the public. Public health agencies must play an increasingly important role in the planning and operational stages of the peaceful applications of nuclear explosives and in the final stage of consumer use of Plowshare-generated products.

There are many long term and long distance ramifications of the Plowshare Program, such as the potential radiological contamination of consumer products that may reach the consumer at long times after the event or at great distances from the site of the event. Criteria for evaluating public exposure to radiation from these products need to be developed based on sound scientific research. Standards for radioactivity in consumer products must be developed in relation to potential exposure of the public. Above all, a clear benefit to the public with a minimum of risk must be shown.

The major purpose of this Symposium on the Public Health Aspects of Peaceful Uses of Nuclear Explosives is to focus attention on the health and safety aspects, present the results of safety analyses accomplished to date and other information necessary to an understanding of the public health aspects, and to identify areas where additional research is required.

A general overview of the total symposium content is presented with emphasis on the relationship of the topics to public health.

INTRODUCTORY COMMENTS

Ladies and Gentlemen, it is my pleasure to be opening speaker for this long overdue Symposium on the Public Health Aspects of the Peaceful Uses of Nuclear Explosives. It is encouraging to see people representing so many diverse disciplines and organizational groups--industry, science, public health, and government--gathered together to stimulate and exchange thoughts concerning the Plowshare Program and public safety. I am sure that a listing of our respective job titles or the prime responsibility of our callings would show the broad concern for the public health and the bountiful effect of nuclear science on human progress, and indicate that the potential applications of atomic energy are many and varied indeed.

For this audience, it is only proper to try, in quantitative and specific ways, to get to the critical factors which determine the real balance between benefits and risks.

Each of you is or may become interested in some specific, some specialized phase of the peaceful uses of nuclear explosives. That is apparent in the various subjects on the agenda of this Symposium. There will be many erudite and introspective papers delivered--these will be conclusive commentary on subjects of primary interest to you individually. We, at this symposium, are prospecting for the wealth of ideas and potential needed to obtain a realistic balance between benefit and risk in the Plowshare program. The speakers on the program will, I am sure, provide us with some specific ideas to increase our knowledge and understanding. But, every recommendation, every constructive suggestion that we can contribute - you and I - will be a supplement to that wealth of knowledge, or will stimulate programs to develop the missing information.

There is never a time when a new idea can be considered superfluous. You and the particular public and private interests you represent as potential users of Plowshare applications are encouraged to share your ideas at this symposium because they should be balanced with public health considerations which will affect industrial applications of Plowshare technology. A clear benefit to the public must exceed the attendant risks, not only as they may be calculated, but also in professional and public opinion. We in nuclear science can take very little for granted. We cannot indulge in the luxury of lapses in our broad surveillance of public health and safety.

In things nuclear, it is not so easy to assume that there is nothing to fear but fear itself. Not all the critics and opponents of the various uses of nuclear resources are inspired by science fiction and screen melodramatics. There are certain valid and reasonable criticisms that must be acknowledged and resolved. The proponents of Plowshare should recognize that even when benefits clearly outweigh the risks, it takes time to convince the related professionals and the public.

The Plowshare program is not new. It dates back to 1957 with the first nuclear event, Gnome.

The Public Health Service, through a Memorandum of Understanding with the Atomic Energy Commission(AEC) concerning off-site radiological safety, has been working with Plowshare since its beginning. The program to date has included numerous device development tests, cratering experiments in various geological media, and one feasibility-type underground natural resource recovery experiment.

The program has been concerned with technological development and has been largely conducted at the Nevada Test Site by AEC contractors. The experimental-developmental nature of the program has entailed stringent safety review and a conservative type of hazards-analysis approach. However, at this time, criticism of pollutants of all types are properly coming to public attention due to intensified industrial development. However, as meritorious as clean air, clean water, and clean food may be, the term "clean" must be translated into criteria and standards which can be designed into industrial developments from the conceptual planning stage. The standards must be finite and measureable, even if expressed in ranges rather than a single number. Although it appears conservative from a health standpoint, terms like "zero" and "undetectable" are not really standards nor are they precise. Rather, they are subject to wide fluctuations depending upon the state of the art of measurement and instrumentation.

It has been my experience in working with everything from nuclear explosions to TV sets that industry will be most cooperative, and can easily afford to be cooperative, if criteria and standards are available at an early stage. Often, safety and health provisions which are overlooked initially cannot be corrected for many years. For example, in another field, there are the provisions in the design of many dams in the Tennessee Valley to fluctuate water levels for malaria control. When the systems were incorporated in the conceptual design, electrical production could be maintained and many of the mosquitoes which could transmit malaria would also be controlled. Without such provisions during the conceptual stage, it would become increasingly expensive to utilize this control technique without affecting the production of power.

Today we are concerned with the future--the transition from development to practical application. For practical utilization to take place, industry and State and local governments must become active partners in the program.

The public health aspects of the Plowshare program deal not only with today, but tomorrow, years from now, and decades from now.

We are talking about two basic types of events:

- Cratering - in which a nuclear explosive is used as an earth moving tool (Sedan, Cabriolet, Buggy, Schooner, etc.).
- Contained underground explosions in which the device is used to break up or increase the permeability of the underground resource strata so that the resource can be recovered and used by man or to provide storage cavities (Gasbuggy; and in the future, Rulison).

Either type presents three potential and basic radiological hazards:

1. Immediate release of event-related radioactivity to the environment. This is primarily a near-in acute situation, but may present chronic problems. It is of primary concern with regard to cratering events where there is an inherent release of radioactive effluent; but it is also relevant to "contained" underground events which might not be contained and/or where there are possible problems of ground water contamination.

We have been working with problems of this type for a long time. In early days, field experience developed the relative importance of radioiodine in milk. Today, we are working to keep abreast of any necessary program reorientation required by changes in device design and emplacement techniques. Recent experience has focused attention upon the extent of radio-tungsten and tritium contamination under various conditions. It is important that public health agencies identify the pathway to people and the standards that are useful in evaluating the exposure of the people in a meaningful and numerical manner.

2. The use of products of the "contained type" of experiments. When nuclear energy is used to increase the availability of oil, natural gas, etc., the resulting products will be contaminated to some extent with radionuclides. These products will be used at times and locations far removed from the event. How much contamination will there be? What standards do we use in terms of samples, analyses, environmental evaluation; and, where necessary, how do we check people to determine the validity of our standards in terms of human exposure? Are any clinical manifestations detectable?

3. The worldwide inventory of radionuclides. Of special concern are long lived nuclides with little inhibition to environmental transport--tritium, carbon-14, krypton-85, etc. Of course, in this area of concern we are talking in terms of decades.

I have indicated three basic areas of radiological concern:

-Radioactive effluent
-Radioactive contamination of consumer products
-Radionuclide inventory of our biosphere

There problems in themselves sound formidable, but this week we will also concern ourselves with ground motion and air blast.

Do the problems of this infant industry--Plowshare--seem insurmountable? I don't believe they are if they are properly focused. And that is why we are here--to get a better insight into and understanding of the Plowshare program and its implications. We are also here to discover the type of information public health people need to make independent but scientifically-based evaluations of proposed projects. If public health agencies are active in this manner, they can provide information which will be useful to the planning groups at an early stage so that plans can be modified with respect both to scientific requirements and to public reaction before opinions are frozen through engineering reports or adverse publicly stated comments.

Concurrent and continuously progressive laboratory and field studies must be pursued in all areas of possible adverse effect to the public health and safety from actual and simulated Plowshare-generated sources. Results of such studies and data compiled in conjunction with non-Plowshare tests or research uses of nuclear energy must be examined for applicability to future activities. For general professional acceptance, these activities must be filtered through professional exchanges in order to refine related public health criteria and translate these into useful design systems for engineers.

Such criteria must also serve as a basis for a systematic method of evaluation between public health agencies so that quantitative comparisons can be made between projections and actual contaminations found in the environment after the project has been completed. The purpose of these projects and the numerous health and safety programs, many of which are conducted on state and local levels as well as on broader national and international scales, is to establish a sound public health basis for effective guidelines, standards and controls in terms of risks versus benefits to the population as a whole and to individuals.

Proposed unique or unprecedented Plowshare applications are screened and superimposed, so to speak, against the existing applicable standards and regulations--and, where incompatible, are re-engineered, re-programmed or, as in certain proposed construction projects, postponed until the technology has been developed to such an extent that the experiment or study is compatible with required public health and safety restraints, which should be kept up to date by the radiation protection agencies.

There is another area of concern. The nature of Plowshare activities implies the need for a concurrent, comprehensive, and candid public education program. And these, in my opinion, should be preceded on both a program and project basis by active interchanges between the public health officials and those responsible for the design of the specific projects. If understanding and mutual respect can be generated between these professional groups, it will be possible to assure the public in an effective way that all possible techniques are being employed to protect them from adverse effects of nuclear detonations.

This symposium is intended to be a thorough public examination of all aspects of Plowshare related to Public Health. Unlike the human body which we subject to periodic physical checkups, the Public Health Programs related to Plowshare must undergo a continuing ahd boldly uninhibited examination. The head and heart and all appendages--the current policies and procedures and processes--must be continuously revitalized so that nuclear explosives tempered with public health safeguards will be available to serve mankind in a constructive and meaningful manner.

The Public Health Service, through its Southwestern Radiological Health Laboratory, is in Las Vegas to participate in Plowshare technology with regard to its public health and safety implications. This group will be available for technical assistance and consultation to the states and other agencies. Its record of 15 years experience in the public health and safety aspects of nuclear tests provides an effective basis on which to develop such aspects of Plowshare technology.

Undoubtedly, you have many questions. Hopefully, they will be answered in some substance in the course of this symposium. At the least, problem areas will be identified so that, by experiment or in some future symposia, they can be effectively resolved.

And lastly, let's be candid. Let's learn something from the teenagers and "tell it like it is."

QUESTIONS FOR JAMES TERRILL

1. From M. Chessin:

   Is the testing program for the nuclear sea level canal compatible with the Nuclear Test Ban Treaty? Shouldn't the general public *per se* be brought into the decision process, in view particularly of the linear response to radiation?

   ANSWER:

   The later designs have reduced the amount of radioactivity released, but if complete control cannot be obtained then the planning will be to make the program compatible either through an interpretation of the present treaty or through some modification of the treaty.

   The public should be made aware of the program and all aspects and this Symposium is one device to do this, though it is aimed principally at the professional who will, in turn, spread the word to others. Many other things can be done in this line and others are already underway, such as the Understanding the Atom pamphlets, etc.

2. From G. W. Adair:

   In the past few years, a great deal of discussion has developed concerning the damage to health, incidents of cancer, pollution of the snow and rainfall in certain sections of Utah. Legislators have presented a resolution condemning all types of testing. How much of the complaints are fact and how much is fiction?

   ANSWER:

   Presumably this is with regard to nuclear testing and not to contamination by other things. The general public, of course, is concerned about all types of pollutants. This is reflected not only in public statements and newspapers, but also by congressional actions such as the Air Pollution Act and the Radiation Control Act of 1968 and the continued questioning presented to the Food and Drug Administration. We are living in an age when everyone is questioning the possible effects of all sorts of pollutants and we must expect nuclear experiments to receive their fair share and some will be based on fact and some on extrapolation not justified by research. Overall, this is a healthy sign and I expect these projects will withstand scientific criticism fairly well.

3. From Don Kurvink:

How can you relate to the public that they should be willing to accept the linear health damage such as genetic damage associated with Plowshare projects?

ANSWER:

I think you begin by explaining to them that there is a certain amount of genetic damage that occurs naturally from many sources and a portion of this is due to natural radiation. Further, we acknowledge that a certain amount of damage may be due to necessary medical x-ray exposure. We must admit the possibility of additional change through nuclear experiments. We are trying to get the Federal Radiation Council to establish a level which will allow the nuclear energy projects and industry to contribute only a portion of the natural radiation exposure to minimize any possible hazard. Each project would contribute only a small fraction of this so the total from all would be only a portion. The total exposure of man from all radiation will continue to be responsible for only a portion of the genetic hazard due to all causes. In the case of radiation, we have large dosimetric experiments on animals which can be checked out and form the basis for a value judgment in this area. The intent of the guidelines would be to keep the risk to humans negligible relative to the benefits that can be obtained.

THE PLOWSHARE PROGRAM

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ABSTRACT

The Plowshare Program was established in 1957 as a research and development program to develop peaceful uses for nuclear explosives. During that year, the basic concepts, which have guided the program, were proposed for using nuclear explosives in large excavation projects, conservation and management of natural resources, and scientific research. Research has been conducted primarily by the Lawrence Radiation Laboratory at Livermore, California; however, substantial assistance has been provided by a number of other government agencies and national laboratories. Sufficient knowledge of the phenomenology of underground nuclear explosions and their effects has been developed to permit consideration of industrial use of such explosions. To this end, the first government-industry cooperative nuclear experiment, Project Gasbuggy, was conducted in December 1967. Additional proposals have been received for using nuclear explosives in stimulating natural gas production from reservoirs of varying characteristics: The storage of natural gas, the recovery of copper from a low-grade deposit, and preparing oil shales for <u>*in situ*</u> *retorting. It is believed that several experiments in each of these fields are necessary to develop a proven technology. The timely development of a nuclear excavation technology for use in large-scale excavation projects is a primary program objective and, although additional research and development are needed, substantial progress has been made in several areas. A capability for predicting crater sizes from single and row charges has been successfully demonstrated. The development of low fission nuclear explosives for use in excavation projects has been very successful. It is believed that such projects can be conducted safely. Large nuclear excavation projects, such as harbors and canals, must be closely examined in view of the restraints of the limited Test Ban Treaty.*

Industry's interest and participation in Plowshare continue to increase and commercial use of nuclear *explosives can be expected in the near future. Legislation to permit the AEC to provide nuclear explosive services commercially has been introduced in the Congress. The potential obligations that the U. S. would assume under the Non-Proliferation Treaty, would commit the U. S. to providing nuclear explosive services to non-nuclear weapon countries when the necessary technologies have been developed. A number of countries have expressed considerable interest in a variety of peaceful uses for nuclear explosions.*

* *

Plowshare is the name given to the program of the U. S. Atomic Energy Commission (AEC) for developing industrial and scientific uses for nuclear explosives. The purpose of this paper is briefly to describe the Plowshare program and to provide a setting for the many related topical papers that follow. In doing so, the history of the program will be summarized, its current status and outlook for the future will be described, and some of the major factors will be mentioned which have a significant influence on the development and growth of the related technologies and their industrial and civil use applications.

There are few people in the world who are not aware of the potentially destructive effects of nuclear explosives when used as weapons, but few people are aware of the great benefits that can be obtained when such explosives are used for peaceful purposes. Never before has man had for constructive purposes the tremendous amounts of energy in low cost, small, and easily transportable packages that are available in nuclear explosives. Energy on a scale never before imagined can be used to accomplish tasks or work heretofore considered impossible or impractical because of excessive costs and time that would be required to bring them to fruition using conventional means. Large excavation projects, such as interoceanic canals, harbors, and transits through mountains, that have been considered technically feasible but impractical using conventional excavation means, can now be considered technically and economically feasible using nuclear explosives. Large masses of rock can be broken and fractured below the surface in preparation for exploitation of mineral resources too low-grade for recovery by conventional means, or for creating means for conserving and managing water resources. A nuclear explosion creates temperatures and pressures in the millions of degrees and atmospheres which are not attainable in laboratories; they also produce fundamental particles and most forms of electromagnetic radiation. New elements that do not occur on earth have been created in nuclear explosions. Einsteinium and Fermium were first identified in the products of a thermonuclear explosion.

Historically, it would be very difficult to determine when and by whom ideas were first put forth on using controlled nuclear chain reactions for peaceful purposes; however, there are clear indications that such ideas and suggestions were in being before Fermi and his group successfully initiated and controlled man's first sustained nuclear chain reaction in Chicago. Detonation of Trinity in 1945, the first nuclear explosion, demonstrated a definite possibility for harnessing the tremendous amounts of energy, that had suddenly become available, for peaceful uses. Scientists informally discussed and explored this possibility and in November 1956, an in-house conference was held on peaceful uses of nuclear explosives at the Lawrence Radiation Laboratory, at Livermore, California, (LRL). In February 1957, the first Plowshare symposium was held to discuss "Industrial Uses of Nuclear Explosives;" the basic concepts proposed at this meeting have since formed the basis for the program. These concepts proposed the possible use of nuclear explosives in large excavation projects, conservation and management of natural resources, and scientific research. In June of the same year, the AEC approved the establishment of a research and development program to develop peaceful uses for nuclear explosives; this was the formal beginning of the Plowshare program. Substantial growth and progress were achieved in the next few years and the Division of Peaceful Nuclear Explosives was established in 1961.

Organizationally, the Division of Peaceful Nuclear Explosives has over-all responsibility for direction and administration of the AEC's Plowshare program, and in carrying out these functions, it draws fully on the talents of the Divisions of Biology and Medicine, Operational Safety, Public Information, Military Application, International Affairs, and other Headquarters' Groups. The chief technical effort in the program is carried out at LRL, but significant research in specific technical areas is being conducted by the Sandia Corporation in Albuquerque, New Mexico, and the Oak Ridge National Laboratory, the Savannah River Laboratory, and the Los Alamos Scientific Laboratory. Other government agencies, such as the U. S. Bureau of Mines, the U. S. Geological Survey, the Environmental Science Services Administration (ESSA), and the U. S. Army Corps of Engineers cooperate and provide assistance in their particular areas of research.

The AEC Nevada Operations Office (NVOO) is responsible for the conduct of all nuclear explosions, including Plowshare experiments and projects and, lately, has become responsible for assisting private companies in defining experiments for developing specific concepts for industrial applications of nuclear explosions. In carrying out field operations for an experiment, especially those related to radiologic safety, NVOO is assisted by the U. S. Public Health Service (PHS) in assuring the safety of the public from the effects of the nuclear explosion; the PHS also provides significant assistance in informing the public. The PHS accomplishes this through its own cadre of health officers assisted by state and local health organizations. The NVOO is also assisted in its safety operations by the Air Research Laboratory of ESSA, the U. S. Bureau of Mines, the U. S. Geological Survey, the U. S. Coast and Geodetic Survey, and other public and contractor organizations.

In the early years of the Plowshare program almost all effort was directed to conducting basic research on the processes and phenomena involved in nuclear explosions. Experiments were planned and conducted, such as Gnome, the first Plowshare nuclear experiment conducted in December 1961, and Sedan, the first Plowshare nuclear cratering experiment, conducted in July 1962. Hundreds of nuclear weapons tests were studied in great detail and relevant data were integrated into a rapidly expanding Plowshare literature. Data were obtained on cratering processes and radioactivity, air blast, seismic effects, cavity growth and collapse, chimney growth and dimensions, extent of fracturing, and ground shock effects. Numerous small cratering experiments using high explosives were conducted in various media for developing an understanding of explosion cratering processes and empirical scaling laws for developing a predictive capability for crater dimensions and other explosion effects. At the same time considerable effort was made in developing and testing clean nuclear explosives and emplacement techniques for reducing the amount of radioactivity that might be released from cratering experiments. Special explosives and techniques were developed for conducting several scientific experiments. Numerous public meetings and symposia were held at which developments in the Plowshare research and development program were presented.

Currently, the underground engineering technology, in which the effects of contained nuclear explosions are utilized, has been developed to the stage where several companies have submitted or are preparing proposals for joint government-industry experiments to investigate the feasibility of several concepts of industrial applications of nuclear explosions. The first nuclear explosion in which private industry participated was the Gasbuggy experiment which was jointly conducted on December 10, 1967, by the government and the El Paso Natural Gas Company. Gasbuggy was designed to test the concept of nuclear stimulation of natural gas from a host rock of low permeability; and although production tests are still being conducted, preliminary results indicate that the experiment has been successful. Additional gas production stimulation experiments each in differing media, at depths up to about 13,000 feet, and with varying yields are being investigated. Similar proposals have been submitted and are in various stages of implementation for testing concepts of using nuclear explosions to fracture a low grade copper deposit in preparation for in situ leaching, to create a storage facility for natural gas, and to fracture oil shale in preparation for in situ retorting.

One of the first industrial proposals made to the AEC was for conducting the Carryall Feasibility Study to determine the feasibility of using nuclear explosives to excavate a transit, wide enough for double railroad tracks and a multiple lane highway, through the Bristol Mountains in the Mojave Desert. The Santa Fe Railway Company and the

State of California joined with the AEC in making the study which indicated the feasibility of such an experiment. The project did not progress beyond the feasibility study because of an incompatibility between the development of the technology and the highway construction schedule. Since then a number of nuclear cratering experiments have been conducted in which significant progress has been made in the development of a nuclear excavation technology. A cratering effects prediction capability, using computers, has been developed which will provide a more accurate means of designing nuclear excavation projects. Simultaneous detonation of five nuclear explosives emplaced in a row, Project Buggy, indicated the feasibility of nuclear harbor and canal excavation.

Looking into the future, we plan to continue our research and development program for developing the technologies required for peaceful applications of nuclear explosions. Basic research will be done to further our understanding of the phenomenology of nuclear explosions and their effects, and we plan to conduct at least one specifically designed experiment to further our knowledge in this field. Activities now in progress will continue as rapidly as possible to develop explosives specifically designed for underground engineering uses and means of producing them at the lowest possible cost. We look to and anticipate increasing private industry participation in joint nuclear underground experiments for developing and demonstrating specific applications should be proven for commercial use in the relatively near future.

In anticipation of this phase, studies are underway for improving procedures for processing proposals and for operational systems, including safety, for conducting projects; some results of these studies are currently in process of implementation. Simplified field equipment systems have been designed and procurement has been authorized for some of the necessary equipment. Evolving from studies and experience by the AEC and private companies is an improved concept for pre-shot and post-shot operations. The AEC is responsible, by law, for conducting all nuclear explosions safely, and procedures under study will permit the government to fulfill its responsibilities and allow maximum participation by private companies. This would be done by the AEC providing guiding criteria and private industry conducting the necessary studies and surveys on which the AEC can make a determination on the safety of the experiment. Such criteria would be dependent on the nature of the experiment and characteristics of each site.

Research and experiments will continue in developing a nuclear excavation technology. We plan to conduct several nuclear cratering experiments to provide a timely determination on the technical feasibility of nuclear excavation for use by the Atlantic-Pacific Inter-Oceanic Canal Study Commission. That Commission is studying the feasibility of using nuclear explosives to excavate a sea-level canal in the American Isthmian region; the schedule for the Commission's final report to the President is December 1, 1970.

Several states have expressed strong interest in the possible application of nuclear explosions for a number of purposes within their areas. Last year, the State of Arizona requested the AEC and Department of Interior to join with the State in conducting a feasibility study for the possible use of nuclear explosives for conserving and managing water resources in Arizona. This study is in progress and is expected to be completed by July 1, 1970. Several of the states in the Appalachian region have considered the use of nuclear explosions to assist in exploiting their mineral and water resources as a means of attracting industry and capital investiment to improve the economic status of the region. Meetings have been held with representatives of the State of Idaho on the possible use of nuclear explosions to produce aggregate for a rock-fill dam near Twin Springs. A symposium on peaceful uses of nuclear energy was recently held in Boise in which several Plowshare papers were presented; the Governor, state legislators, the Idaho Nuclear Energy Commission, the Idaho Water Resources Board, and representatives of civic and industrial groups participated. We have been encouraged by the active interest of these states and look forward to others participating in our program. Cooperation of states in the Plowshare program is considered essential for the successful conduct of necessary experiments and later, commercial application of nuclear explosives.

Although the Atomic Energy Act permits the AEC to conduct experiments and demonstrations of peaceful applications of nuclear explosives, the AEC is not now authorized to provide explosion services on a commercial basis. Congressman Craig Hosmer, from California, considering the progress made in the AEC's Plowshare program and the proximity of the application of nuclear explosives on a commercial basis, last year authored legislation which would authorize the AEC to provide commercial Plowshare services. This legislation was introduced in both Houses of Congress during its last session. This legislation has been reintroduced in the current session. Public hearings were held by the Joint Committee on Atomic Energy last year at which time government and industrial officials appeared before the Committee or submitted statements favorably endorsing the legislation. It is anticipated that hearings will be held this year. Should the enabling legislation subsequently be enacted it would be a significant step toward the goal of providing a useful and economic explosion service to users of Plowshare technology.

Enactment of legislation permitting the AEC to provide commercial nuclear explosion services also would facilitate providing such services to foreign countries under Article V of the Non-Proliferation Treaty. Article V states, "Each Party to the Treaty undertakes to take appropriate measures to ensure that, in accordance with this Treaty, under appropriate international observation and through appropriate international procedures, potential benefits from any peaceful applications of nuclear explosions will be made available to non-nuclear-weapons States Party to the Treaty on a non-discriminatory basis and that the charge to such Parties for the explosive devices used will be as low as possible and exclude any charge for research and development." The nuclear explosives would remain under the custody and control of the nuclear-weapon state, which would, in effect, provide a nuclear explosion service.

Such a service would be for those peaceful applications that have been proven technically and economically feasible and are permissible under the limited Test Ban Treaty. The latter prohibits all nuclear explosions which cause, "radioactive debris to be present outside of the territorial limits of the country under whose control or jurisdiction such explosion is conducted." The restraints of this treaty will be an important and, perhaps, controlling factor on applications of nuclear excavation such as harbors, interoceanic canals, and other excavation projects in proximity to country borders.

As Plowshare technologies are developed and are commercially applied in domestic and foreign industrial fields there will be an increasing demand for engineers and scientists with training and experience in nuclear explosive engineering. It is very important to the realization of Plowshare goals that adequate numbers of such personnel become available to private industry and federal and local governments beginning in the very near future. This requirement was early recognized by several universities, and plans were developed and implemented to include appropriate courses in both undergraduate and graduate schools. Currently, definitive courses in nuclear explosive engineering are offered by the Stanford University, the University of California at Davis, and the Pennsylvania State University. Closely related courses and subjects are offered at the University of Michigan, University of Arizona, University of Puerto Rico, and Iowa State University. Other colleges and universities are seriously studying the matter. On March 31 and April 1 and 2, a symposium on "Education for Peaceful Uses of Nuclear Explosives," was held in Tucson, Arizona. In addition to papers on the status and technological requirements of nuclear explosives and explosion engineering, excellent presentations were made on related educational programs, university research and manpower needs, and development of educational means to meet the growing need for Plowshare related engineers and scientists. The AEC very much appreciates the efforts that have been made to include Plowshare related courses in college and university curricula and urges that such efforts be increased and expanded to include other schools; in this connection, the AEC will cooperate and provide whatever assistance it can. It is appropriate at this point to suggest that it be recognized that there is a difference between nuclear explosive and nuclear explosion engineering. The former should be concerned with the design and development of nuclear explosives with characteristics specific to the needs of the various applications. Nuclear explosion engineering should be concerned with the safe and economic application of the effects of nuclear explosions.

Industrial applications of nuclear explosions have received considerable attention by the Atomic Industrial Forum (AIF), American

Nuclear Society, (ANS), and other professional and industrial groups. The AIF held an "International Conference on Constructive Uses of Atomic Energy" concurrently with a session of the ANS winter meeting in Washington, D. C., in November 1968. Government and industry spokesmen reviewed the status of industrial participation in the Plowshare program and identified several areas in which such participation could be expanded by simplified government procedures, establishment of safety criteria, and release of more Plowshare information.

The AIF has established a Committee on Industrial Plowshare Applications to study and make recommendations on industry's participation in developing and applying industrial Plowshare technologies. Five subcommittees were organized with specific areas to be investigated and studied. The AEC is cooperating with these groups and anticipates considerable assistance from them in establishing appropriate government-private industry relationships to foster greater industry participation in experiments and establish procedures for commercial application of Plowshare technologies.

Foreign interest in Plowshare and awareness of its potential benefits began during the early years of the program. Numerous suggestions for applications have been received from foreign countries and information provided on request. Several countries have sent groups to the U. S. for orientation meetings and visits to the laboratories and field offices.

Australia, from an early date, has been very interested in the Plowshare program and, as a result of an evaluation of the program by three Australian government officials in 1963, determined at that time, that with further development of the related technology, nuclear explosions could assume a significant, if limited, role in the construction of major works and the exploitation of mineral resources in that country. Recently, the Government of Australia requested the U. S. Government to participate in a study to determine the technical and economic feasibility of conducting an experiment to create a harbor with nuclear explosives near Cape Keraudren on the northwest coast of Australia. The U. S. agreed to participate, and assigned to the AEC the task of carrying out U. S. responsibilities. A series of meetings was held with representatives of the respective governments and the mining company, which would utilize the harbor, to define the proposed feasibility studies. The mining company reevaluated its need for a harbor and indicated its desires to limit its participation in the studies. Since the economics of the mining venture would be an essential element, the Australian and the U. S. Atomic Energy Commissions concluded that there would be insufficient basis for proceeding with the proposed studies. They continue to be interested, however, in the possible use of nuclear explosions for harbor construction and will continue their review of the practicability of applying this technology to other possible harbor sites in the area.

Whether Plowshare experiments or industrial application projects are planned to be conducted on foreign or domestic sites, their actual execution will depend on their acceptance by the public. The public is acutely aware of the potentially harmful effects of nuclear explosions and it is easily understandable that many people should view all such explosions as unnecessary except those related to national security. This was recognized very early in the Plowshare program and extensive, continuing efforts were initiated to educate the public on the benefits to be achieved through peaceful uses of nuclear explosives and the great care that is taken to assure that effects of the explosions do not create hazards to the safety of the public. The general public acceptance must be obtained for Plowshare experiments and industrial projects in general, however, the acceptance of the public in regions and local areas in which the detonations are planned is most critical. To achieve this acceptance, the public must be kept fully informed of the nature of the proposed project; its purposes and anticipated benefits; how, when, where, and by whom it is to be conducted; the accuracy of predicted effects and the soundness of evaluations of those effects on people and manmade and natural objects; and the efforts that will be taken to prevent those effects from becoming hazards.

The health and safety aspects of the Plowshare program are not elements apart from the technical and economic aspects. The cost of safety is an integral part of the feasibility of any application, in the same way as in the cost of, say, drilling the emplacement hole. Just as one wants to drill the hole in the most economic manner, one wants to assure safety in the most economic manner. Just as a smaller cheaper hole which will not accommodate the explosive is useless to the user, a safety program which considers only cost is worthless. Carrying the analogy one step further, just as much effort and thought is expended in learning how to drill holes for less money, similar effort and thought must be expended so as to assure safety at least cost.

Plowshare is a multifaceted program. It draws on many fields of knowledge. Symposia such as this one provide the public with the opportunity to understand how all phases of the program move forward together, cross-feeding information to each other. In addition, symposia and public meetings, such as this one, have proven to be an effective means of informing all members of the public, including the scientific and engineering regimes, educational institutions, news media, and the great numbers of the general public. It is hoped that the information presented and made available to the public through this symposium will be helpful to the public in obtaining a better understanding and acceptance of our program.

QUESTIONS FOR RICHARD HAMBURGER

1. From M. Chessin:

   In view of Dr. Terrill's comments about contamination of underground materials such as produced by projects such as Gasbuggy, what has been the fate of gas produced by Gasbuggy?

   ANSWER:

   The gas from Gasbuggy was flared under controlled conditions. This was done in such a manner as to not exceed appropriate atmospheric concentration guides. None of this gas has been released for commercial or public use.

2. From Dr. N. Simon:

   You stated, "Gasbuggy was a success." By what criteria from a public health aspect? Are there data on contamination of gas or environment?

   ANSWER:

   I meant that Gasbuggy was a success in the sense that it accomplished the primary purpose of increasing gas production at that site. As far as contamination of the gas or environment, data from this project will provide answers which will be used in the design of future experiments so that any hazard can be reduced to negligible proportions.

3. From Kenneth Kase:

   Is DPNE doing anything to establish criteria for siting Plowshare projects similar to the Reactor Siting Criteria?

   ANSWER:

   I am not sure I understand fully what is meant by that question as I am not familiar with reactor siting criteria. We are working on safety criteria for Plowshare events, and this is not limited to radionuclides but also includes shock damage and underground water contamination.

4. From R. A. Nelson:

   What are the interests of the insurance companies in the Plowshare program now and in the near future in providing liability and property damage coverages to the commercial users of nuclear explosives?

ANSWER:

The insurance companies, as far as I know, are looking into the possibilities of providing coverage for these projects.

5. From R. A. Nelson:

Do you know if NELIA (Nuclear Energy Liability Insurance Association) has been involved in this Plowshare program to provide the coverages needed?

ANSWER:

I do know that they have been asking for information though there is little enough experience on which to base rates, but I believe the Association would be the proper agency to address this question to.

6. From Dr. Robert B. Medz:

Reference was made to increase permeability of sub-surface rock structures. What are the public health risks involved in contamination of underground waters from deep well waste disposal practices as a consequence of this increased permeability?

ANSWER:

There are really two factors to be considered here. First, ground water entering the permeable space would block gas flow and so defeat the purpose of gas stimulation experiments. Also, from a public health standpoint, contamination of ground water must be minimized. For these reasons, such experiments are carefully planned to eliminate these possibilities. This would also apply to deep well waste disposal practices.

7. From C. L. Pringle:

Is DPNE funding studies on maximum permissible concentrations for consumption of gas?

ANSWER:

We are funding studies by various organizations which will provide information on which to base criteria such as the maximum permissible concentration in the gas for public use, and these will be done carefully before any such use is permitted.

8. From Mr. T. Otsubo:

What is the feasibility of nuclear explosive application to exploration of such mineral mines as copper, lead and zinc underground?

ANSWER:

I think the answer to that is there is not too much of an application to the exploration of minerals, but there is for exploitation of certain ores such as those which can be leached in situ or which can be recovered by caving operations.

SESSION II - PLOWSHARE APPLICATIONS, EXPERIMENTS AND RESULTS

Chairman: Mr. Richard Hamburger
Assistant Director, DPNE
U. S. Atomic Energy Commission
Germantown

NUCLEAR CRATERING APPLICATIONS

M. M. Williamson
U. S. Atomic Energy Commission
Germantown, Maryland

ABSTRACT

The development of nuclear excavation technology is based on the premise that the relatively inexpensive energy available from thermonuclear explosives can be used to simultaneously break and move large quantities of rock and earth economically and safely. This paper discusses the economic and other advantages of using nuclear excavation for large engineering projects. A brief description of the phenomenology of nuclear excavation is given. Each of the several proposed general applications of nuclear excavation is discussed to include a few specific examples of possible nuclear excavation projects. The discussion includes nuclear excavation for harbors, canals, terrain transits, aggregate production, mining and water resource development and conservation.

* *

Throughout his history, man has searched for new and better means to break and move rock and earth. His search has progressed from hitting one rock with another and using his hands to scoop up the broken pieces, to breaking rock with explosives and moving the broken pieces with huge earth-moving and digging machines which can handle 100 cubic yards or more with a single bite. These were the tools of excavation until the detonation of the first nuclear explosion, in 1945, opened the possibility for the development of a tremendous new excavation tool. The successful detonation of the first thermonuclear device heightened these possibilities even further by demonstrating that nuclear explosives could utilize the cheaper fusion fuels, with the bonus of less by-product radioactivity than with fission fuels. It is not unusual that such a tool should be born as a tool of war. The first explosive, black powder, was also born as a tool of war and explosives existed for over six hundred years before being applied to peaceful purposes. It seems encouraging then, that less than twenty-five years after the first nuclear explosion, man is actively engaged in developing this huge energy source as an engineering tool for peaceful purposes.

The development of nuclear excavation technology is based on the premise that the inexpensive energy available from thermonuclear explosives can be used to simultaneously break and move large quantities of rock and earth economically and safely. It is considered possible, with the development of nuclear excavation technology, to use nuclear energy to perform the excavation required for large engineering projects such as canals, harbors, cuts through mountain barriers, and other large excavations that might not otherwise be done. Nuclear excavation, both domestic and international, appears, in some cases, to offer potential cost savings in the hundreds of millions of dollars and significant reductions in construction time. Indeed, in many large earth-moving concepts, the financial requirements, extending over long periods of time, make the excavations economically infeasible with current earth-moving systems. The nuclear explosion, as a new, relatively cheap excavation tool, may make such concepts much more attractive.

The inherent advantage of using nuclear explosions for excavation lies in the huge energy source available in a small package and at low cost per unit energy released. This advantage is manifest at a few kilotons yield (equivalent to a few thousand tons of TNT) and becomes increasingly apparent at greater yeilds. To illustrate the economic attractiveness of nuclear explosives as energy sources, one can use the projected charges for thermonuclear explosives released by the Atomic Energy Commission in 1964 (Figure 1). These projected charges, which were released only for use in feasibility studies and evaluations, are based on a projection to a time when thermonuclear explosives would be produced in quantity for routine commercial utilization. The charges cover nuclear materials, fabrication and assembly, and arming and firing services, but do not cover significant related services such as safety studies, site preparation--including construction of holes, transportation and emplacement of explosives, and support. The latter services, of course, depend significantly on the number of explosives detonated at a given location. As can be seen, the costs of the explosives on a per ton basis, range from $35/ton for a 10 Kt explosive, down to $0.30/ton for a 2 Mt explosive (equivalent to 2 million tons of TNT). As a comparison, dynamite and TNT cost $400-$500/ton.

Thermonuclear explosives designed for nuclear excavation can be expected to be of a size which could be emplaced in

48 to 72 inch diameter holes. In contrast, 10,000 tons of TNT, in its most compact form, a sphere, would require a hole over 80 feet in diameter. If one envisions an engineering project of a size requiring a few hundred kilotons of explosives, the logistics problems of producing, transporting and emplacing the required quantities of chemical explosives become staggering. This, of course, is one of the reasons chemical explosives are not used in this manner.

Although there are engineering projects in the United States and other highly industrialized nations, where nuclear explosives may be used to advantage, the potential economic advantages of engineering with nuclear explosives are even more pronounced in many less industrially developed areas. In many such areas, the cost of importing new equipment or diverting existing industrial capacity to support large earth-moving projects limits the capability to accomplish such work and thereby impedes development. Of course, the choice of construction method on any project must depend on an analysis and comparison of the alternative means available, and must consider the total requirements necessary to produce a completed project with a given energy system. In general, one can say that the types of projects for which nuclear explosives are most likely to be an advantageous energy source, are those which require excavation of rock in sufficient volume to require yields approaching 10 kilotons or larger, or those which require large excavated cross-sections near 100 meters in depth, in soft materials such as alluvium.

Before discussing several proposed applications of nuclear excavation, it is necessary to understand a few generalities of the phenomenology of nuclear excavation and to become acquainted with a few of the terms. Depth of burst (dob) is the term used to delineate the distance below the ground surface at which the explosion takes place. Optimum depth of burst is that depth of burst at which crater dimensions are maximized. This, of course, is a function of the yield of the explosive and the characteristics of the material in which the explosion takes place. Figure 2 illustrates the sequence of events in a nuclear cratering explosion. When the explosive is detonated, extremely high temperatures and pressures are generated and the rock immediately surrounding the explosion point is vaporized. At the same time a compressional shock wave radiates spherically from the explosion point doing work in the form of crushing compaction and plastic deformation. Upon reaching the free ground surface, the shock wave is refracted back toward the explosion point, placing the rock in tension. If the sum of the outgoing compression wave and the refracted wave exceeds the tensile strength of the rock, the rock will fail in tension and pieces will fly off with a velocity characteristic of the momentum trapped in the "spalled" piece of rock. As the rarefaction wave returns to the cavity, it reinforces the high pressure gases pushing on the walls of the cavity. The cavity expands asymmetrically toward the surface, folding back, accelerating and ejecting much of the overlying material and allowing the explosion gases to filter through the disassembled mound. As the cavity pressure is relieved, the material which received insufficient horizontal components of velocity to eject it from the excavation, falls back into the crater. Enough material is ejected, however, to leave an excavation of considerable volume; over 6 million cubic yards in the case of the 100 Kt Sedan crater, a Plowshare experiment in 1962.

If the explosion takes place somewhat deeper than optimum cratering depth, the sequence of events (Figure 3) is essentially the same up to the point of disassembly of the mound but the visible effects on the surface are altered. In this case, the explosion is deep enough so that the shock wave has been attenuated to a great degree before reaching the surface and the effects of spalling are reduced. The cavity pressure is relatively lower just prior to mound rupture, the cavity stops growing and the overlying material collapses into the cavity. Little or no material is actually ejected from the excavation. If the material has a bulking factor somewhat greater than one, as does most rock, it will occupy a greater volume when broken than it did *in situ*. If the bulked volume of the collapsed material is greater than the cavity volume, the surface manifestation of this mode of emplacement is a mound of broken rock. On the other hand, if the volume of the collapsed material plus the volume of the void spaces is less than the cavity volume, the collapsed material will not fill the cavity completely and the surface manifestation will be in the form of subsidence, termed a subsidence crater. When the detonation is at a much deeper depth of burst, the collapse does not propagate to the surface and the only surface manifestation may be a very broad dome raised some few inches to tens of inches in the center.

All three types of excavations, ejects, bulk, and subsidence craters, may be used for potential nuclear excavation applications. However, before discussing these potential applications, it should be pointed out that no proposed nuclear excavation application is in an active stage of planning for execution. The transisthmian sea-level canal proposal is in a feasibility study stage and no decision will be made regarding its construction until after the Atlantic-Pacific Interoceanic Canal Study Commission has reported to the President, now scheduled for December 1, 1970. Another feasibility study to determine possible uses of nuclear explosions for water resource development in Arizona is now in progress. All other applications which will be mentioned are merely suggestions from individuals, private consultants, engineering firms, etc. (Bibliography 6, 7, 8, & 9); suggestions which have been reviewed in more or less detail to determine if they might be suitable projects. No project would be undertaken, of course, without a detailed economic and technical (including safety) feasibility study, and then further study, if feasibility were established, to enable design of technical, safety, support, and other requirements.

Probably the most widely known of the applications for which nuclear excavation is being considered is the construction of canals (Figure 4), specifically the construction of a sea-level canal across the American Isthmus. The Atlantic-Pacific Interoceanic Canal Study Commission, established by the 88th Congress, is charged with determining the feasibility of, and the most suitable site for, the construction of a sea-level canal connecting the Atlantic and Pacific Oceans; the best means of constructing such a canal, whether by conventional or nuclear excavation, and the estimated cost thereof. The Chief of Engineers of the U. S. Army Corps of Engineers has been designated as the Engineering Agent for the A-P/ICSC and the Corps of Engineers is developing on-site information in such fields as geology, hydrology, topography, and hydrography. The U. S. Atomic Energy Commission is developing data in such fields as meteorology, seismology, and ecology for use in the nuclear safety studies and, of course, through the Plowshare program is providing information on the technical feasibility of nuclear excavation. Three nuclear cratering experiments, Cabriolet, Buggy, and Schooner, were conducted in 1968 as part of the nuclear excavation research and development program which provides information to the canal studies.

The concept for nuclear excavation of a long canal, such as a transisthmian canal, is depicted in Figure 5. Since the total excavation might require 300 or so explosives with a combined yield of 200 or 300 Mt (depending on the route selected, geology, and many other parameters), one would not propose to excavate the entire length in one blast because logistics, safety, and other considerations could become unmanageable. If one were to attempt to drive the canal straight through, without skipping alternate sections, the personnel working in the section immediately adjacent to the section where a detonation was imminent, would have to be evacuated during the detonation. The detonation would collapse some of the emplacement holes in the adjacent section if they had been predrilled. The base surge from the detonation would cover a portion of the adjacent section resulting in some radioactivity deposition. Workers would have to wait for the radioactivity to decay before they could return to that portion of the adjacent section to prepare it for the next detonation.

Therefore, the leap-frog concept has been suggested wherein the total yield of a string of explosives would be limited to, perhaps, a few megatons. Such a concept would not only enable control of ground motion, air blast, and radioactivity effects but, would also allow drilling crews to prepare emplacement holes in alternate sections up the line at the same time that emplacement and detonation operations were in progress on previously drilled sections. By the time the first pass across the canal route was completed, residual radioactivity levels from deposition on the first unexcavated sections should be very low and workers could safely enter and start preparing them for detonation, and then proceed on across the route in the same manner as before to complete the excavation.

Although a transisthmian sea-level canal is the best known proposal, other canal projects have been suggested as possible projects suitable for nuclear excavation. A canal across the Isthmus of Kra on the Malay Peninsula could cut 500 miles or more from the shipping lanes between India and the United States and Japan. Such a canal might be about 30-50 miles long and would go through areas with elevations ranging from sea-level to about 900 feet above sea-level. Canals across the Alaskan Peninsula and across the Boothia Peninsula in Northern Canada have been suggested in order to shorten shipping lanes to the north and west coasts of Alaska and Northern Canada.

Nuclear excavation has also been proposed as a means of removing barriers to shipping in otherwise navigable channels. As examples, the removal of rapids in the Madeira River in Brazil could permit river transportation from the Amazon to interior locations in Brazil, Bolivia, and Peru; elimination of shoals on the Paraguay River could provide freer navigation to Asuncion; clearing the delta of the Mackenzie River in Northern Canada could be important to the development of Arctic North America.

Nuclear excavation for canals might also be applicable to the diversion of water directly for, or to facilitate, construction of hydropower projects. One proposal envisages connecting the Qattara Depression in Northern Egypt to the Mediterranean Sea by a canal. The depression lies at a depth of about 164 feet below sea level and the hydrostatic drop might be used for power generation. Evaporation would be sufficient to maintain the drop for several hundred years. Nuclear excavated canals could also be used for stream diversion during conventional construction of dams or to divert streams into canyons where dams have been previously constructed in the dry.

Another reason for stream diversion is to get water from water-rich to water-poor areas. A nuclear excavated canal has been suggested as a means to divert water from the Niger River to the Volta River Basin, thereby recovering some 33 million acre-feet of water annually, amking it possible to irrigate 2 million acres of land in Mali, Ghana, and Upper Volta. The proposed canal would be about 50 miles long through a maximum cut elevation of about 500 feet. A diversion of the Sao Francisco River in northeastern Brazil has been suggested, to bring water 40 miles through a mountain range for irrigation of an estimated 200,000 acres of land. A suggestion has been made to divert water from the eastern slopes of the Andes to arid western slopes. Studies have been conducted to divert water from Northern California to the Central Valley of California and to water-poor Southern California. Portions of this network might be suitable for nuclear excavated canals.

Other water resource development and management projects could possibly use nuclear excavation in the form of craters for water storage (Figure 6) and ground water recharge (Figure 7); crater lips for dams (Figure 8); strategically located explosions for ejecta and bulk dams (Figure 9); and explosions to produce aggregate for rock fill and concrete dams (Figure 10). A feasibility study known as Aquarius is being conducted to determine if nuclear explosions may be suitable for use in developing and managing the water resources of Arizona. This study is a joint effort of the State of Arizona, primarily through the Arizona Atomic Energy Commission, the Department of the Interior, primarily through the Bureau of Reclamation, and the USAEC, with the assistance of the U. S. Army Corps of Engineers' Nuclear Cratering Group. The study is planned for completion before the end of this year.

Some of the most arid areas of the world, much drier than the Southwestern United States, are not dry all the time, but rather are subjected to infrequent but torrential rainfalls. An outstanding example of such areas is the desert areas of Australia. Nuclear excavated craters might be used as catchment basins to collect and store the water from these rainfalls for use during the dry seasons. Nuclear explosions might also be used to advantage in opening or closing mountain passes and providing diversion canals to deflect streams from the wetter coastal regions to the interior deserts. Also, numerous proposals have been made for dams and diversion canals on the Indus and Ganges Rivers in Pakistan and India to aid flood control and irrigation.

A special type of ejecta or throwout dam has been suggested for construction in deep, steep-walled canyons such as are common in the rugged mountains of Alaska. In this case the explosion would take place in the wall of the canyon directing the ejecta across the canyon floor. In addition to the material thrown into the canyon, the material on the upper edge of the side-lying crater would be expected to collapse and spill additional rock onto the embankment. This technique has been successfully demonstrated by the Soviet Union wherein a 2.6 million cubic yard rock fill dam was constructed across the Vakhsh River using 2,000 tons of chemical explosives buried in the side of the steep-walled canyon. A very similar technique has been demonstrated by nature in cases like the slide dam on the Madison River in Montana. In this case, an earthquake triggered a landslide which flowed across the canyon and dammed the river. Man then gave an assist by cutting spillways to prevent erosion, much as would have to be done on a dam constructed by nuclear excavation.

The U. S. Army Corps of Engineers has identified areas in the Western U. S. where nuclear explosives might be used to advantage for producing aggregate for rock-fill or concrete dam construction. This technique envisages breaking the rock with nuclear explosions and recovering the broken rock with earth-moving equipment for further use in constructing the dam (or satisfying some other large demand for aggregate).

Cuts through mountain barriers would be possible using the same nuclear techniques as for canals. Figure 11 shows a model of such an excavation to accommodate a railroad and superhighway passage. Note the crater on the right of the main excavation to serve as a catchment for runoff water. One possible application of this technique which has been studied in some detail, is a cut to accommodate the realignment of Interstate Highway 40 and the Atchison, Topeka, and Santa Fe Railroad through the Bristol Mountains in California. Another is the realignment of the Southern Pacific Railroad through Boca Pass near Lake Tahoe in Northern California. Several proposals have been made for nuclear excavations for road beds in Colombia, Argentina, and Chile.

Figure 12 shows an artist's conception of a harbor and entrance channel excavated with nuclear explosions. Many areas of the world are known to have rich mineral resources which are not economically recoverable because of the lack of transportation. Construction of harbors on otherwise harborless coastlines could provide shipping access, and lead to development of the areas. Notable among these areas is Western Australia. Recently, the Government of Australia invited the Government of the United States to participate in carrying out a study of the technical and economic feasibility of using nuclear explosions to excavate a deep-water harbor at Cape Keraudren on the northwest coast of Australia. The United States agreed to participate in the feasibility study. Subsequently, the Sentinel Mining Company completed a reevaluation of its opportunities in the mining and marketing of iron ore, which was to be the principal product shipped through the proposed harbor, and decided to limit its participation in the study. Since the economics of the mining venture was an essential element, it was decided that there was insufficient basis for proceeding with the study. However, the U. S. and Australian Atomic Energy Commissions continue to be interested in the possible use of nuclear explosions for harbor construction and will continue their review of the practicability of applying this technology to other possible harbor sites in the area.

The concept for this type harbor is an interesting one for possible application in areas where the sea bottom slopes gently away from the shoreline, thus limiting access by large ships to some few miles from the shore due to the shallow depth of water. Figure 13 shows an artist's rendition of a concept for such a harbor. The concept envisages detonation of 5 explosives, each with a yield of 200 Kt buried about 1,100 feet apart and 800 feet beneath the ocean floor. The resulting crater would be expected to be about 6,000 feet long, 1,300-1,600 feet wide and 200-400 feet deep in the center. The side lips of the crater would be 200-300 feet high and end lips would be 30-60 feet high. Since the water is quite shallow for some distance off-shore, a channel would be dredged to the harbor and cut through the end lip by conventional means. Excess material from the crater lips would provide fill for a causeway to the mainland. The crater would provide a protected harbor for ships up to about 150,000 DWT.

Other possible harbor excavations have been suggested in Chile, Somalia, Peru, several in Alaska, and several in Australia. The recent North Slope Oil discoveries in Alaska have caused renewed interest in developing transportation to Northern Alaska. The logistics advantages of nuclear excavation for construction in such isolated areas seems obvious, however, construction by any means in permafrost areas is known to be a tricky proposition.

Figure 14 illustrates the use of nuclear explosions to strip overburden from mineral deposits to facilitate open-pit mining. This technique has been suggested for use in several areas of Colorado, Utah, Arizona, and Wyoming.

Figure 15 shows still another possible technique for using nuclear explosions to aid in recovery of mineral deposits. In this technique the explosion would take place at a depth which would produce a mound of broken rock in a shallow ore body. Leach liquor would be introduced at the surface, drain through the ore-bearing rubble and leach out the mineral. The pregnant liquor would then be pumped out from the bottom, processed to remove the mineral and the clean leach liquor recycled.

In summary, the possible applications of nuclear excavation are many and varied; development of transportation routes and facilities through construction of harbors, canals, cuts through mountainous terrain and removal of navigation barriers; development and management of water resources through construction of diversion canals, storage reservoirs, dams and ground water recharge facilities; and development of mineral resources through overburden removal and *in situ* leaching. The potential economic advantages of nuclear explosives for excavation are based on the huge amount of energy which is available in a small package at relatively low cost and which can be used to simultaneously break and move rock. The advantages are most pronounced in undeveloped areas or areas in the infancy of development, where logistic, industrial, and long-term financial support would be strained or totally insufficient to allow development with present-day construction methods. In this light, the development of nuclear excavation technology should provide man with an extremely useful and powerful engineering tool.

BIBLIOGRAPHY

1. Hamburger, Richard, "The Use of Peaceful Nuclear Explosives and Some Related Safety Aspects," U. S. Atomic Energy Commission, reprinted from Proceedings of the Seventy-First Annual Meeting, United States Livestock Sanitary Association, 1967.

2. Hughes, Bernard C., "The Corps of Engineers Nuclear Explosives Studies for Civil Construction," Tech. Report No. 8, U. S. Army Engineer Nuclear Cratering Group, Lawrence Radiation Laboratory, Livermore, California, October, 1968.

3. Nordyke, M. D., "Concept for a Demonstration Harbor at Cape Keraudren, Western Australia," DRAFT University of California, Lawrence Radiation Laboratory, Livermore, California, January, 1969.

4. Nordyke, M. D., "On Cratering. A Brief History, Analysis, and Theory of Cratering," UCRL-6578, University of California, Lawrence Radiation Laboratory, Livermore, California, August, 1961.

5. Nordyke, M. D. and M. M. Williamson, "The Sedan Event," PNE 242F, U. S. Atomic Energy Commission, April, 1965.

6. Sanders, Ralph, *Project Plowshare,* Public Affairs Press, Washington, D. C., 1962.

7. Teller, Edward, "Plowshare," UCRL-7222, University of California, Lawrence Radiation Laboratory, Livermore, California, February, 1963.

8. Teller, Edward and Wilson K. Talley, Gary H. Higgins, and Gerald W. Johnson, *The Constructive Uses of Nuclear Explosives,* McGraw-Hill, 1968.

9. Numerous private communications.

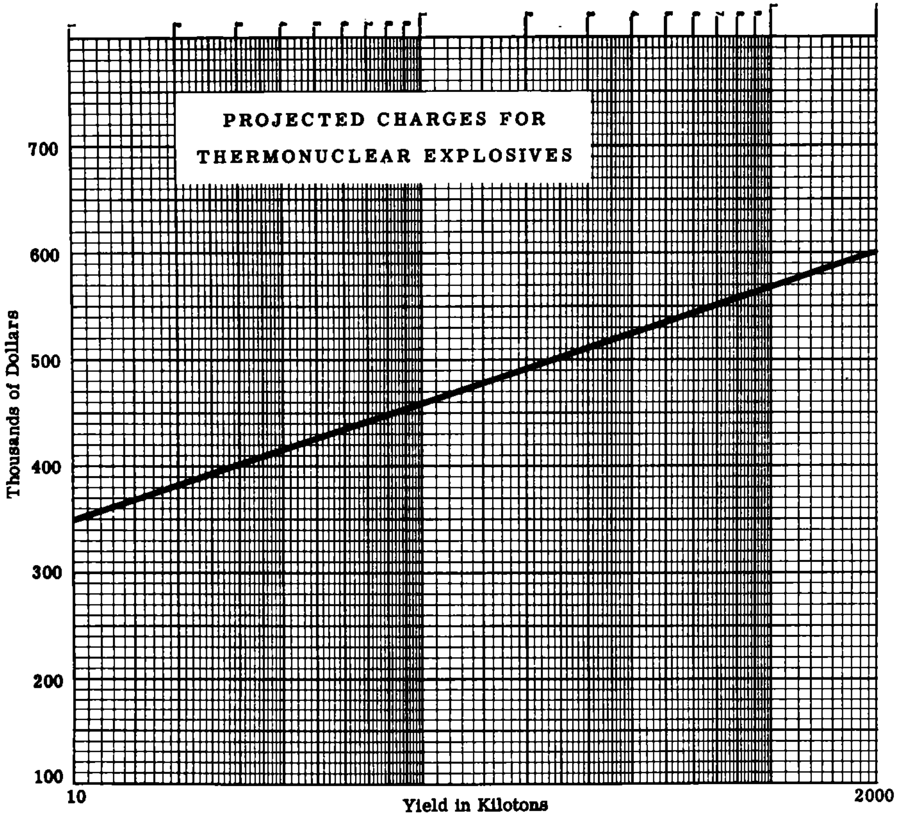

PROJECTED CHARGES FOR
THERMONUCLEAR EXPLOSIVES
Thousands of Dollars
700
600
500
400
300
200
100
10
Yield in Kilotons
2000

FIGURE 1

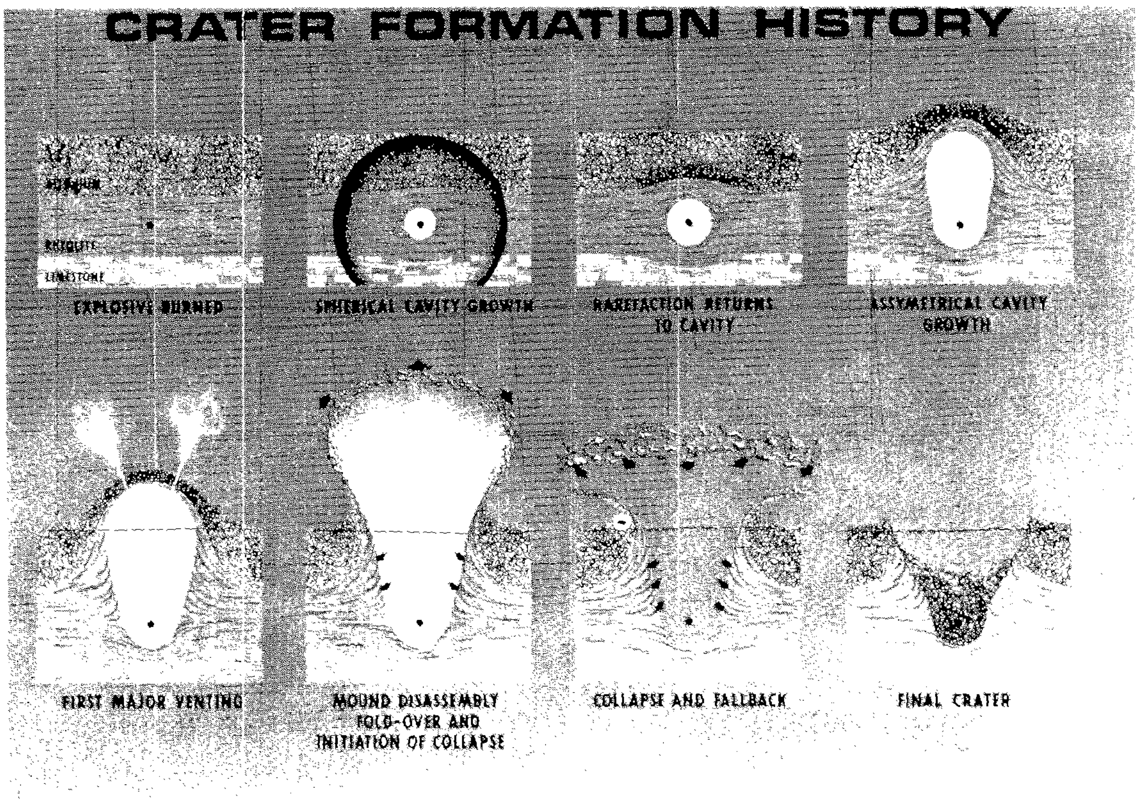


FIGURE 2

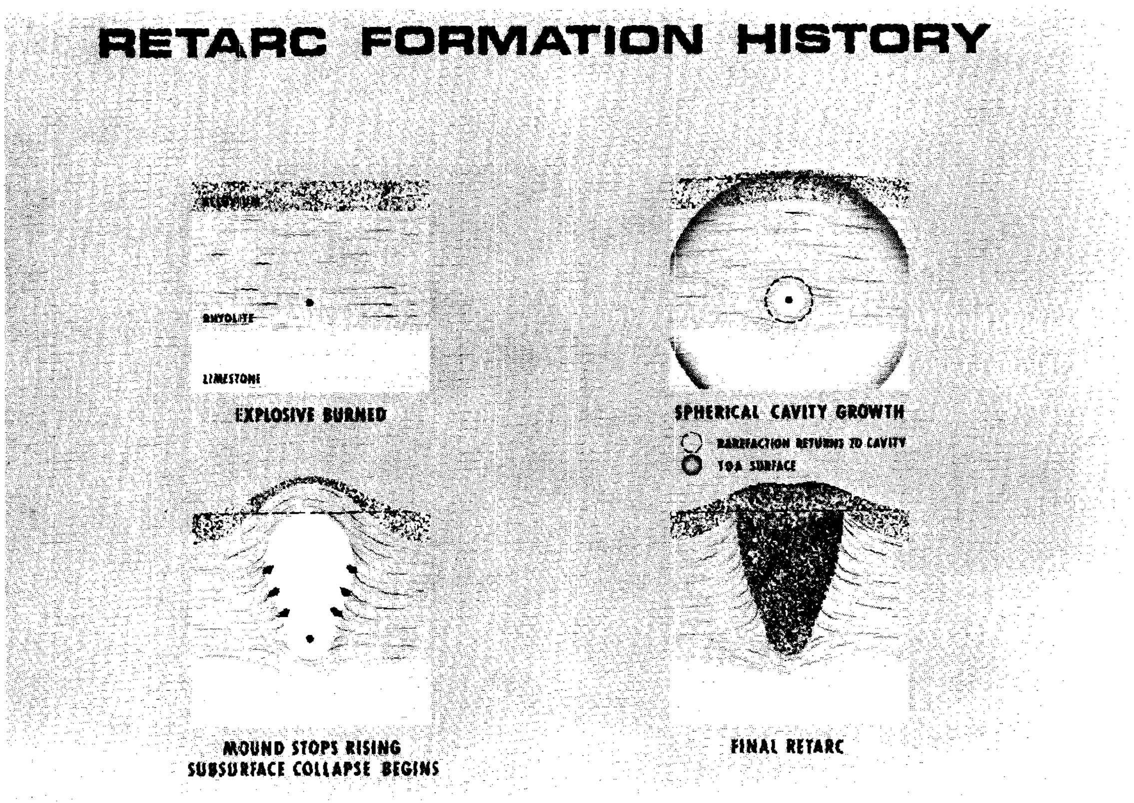


FIGURE 3

NUCLEAR EXCAVATED CANAL

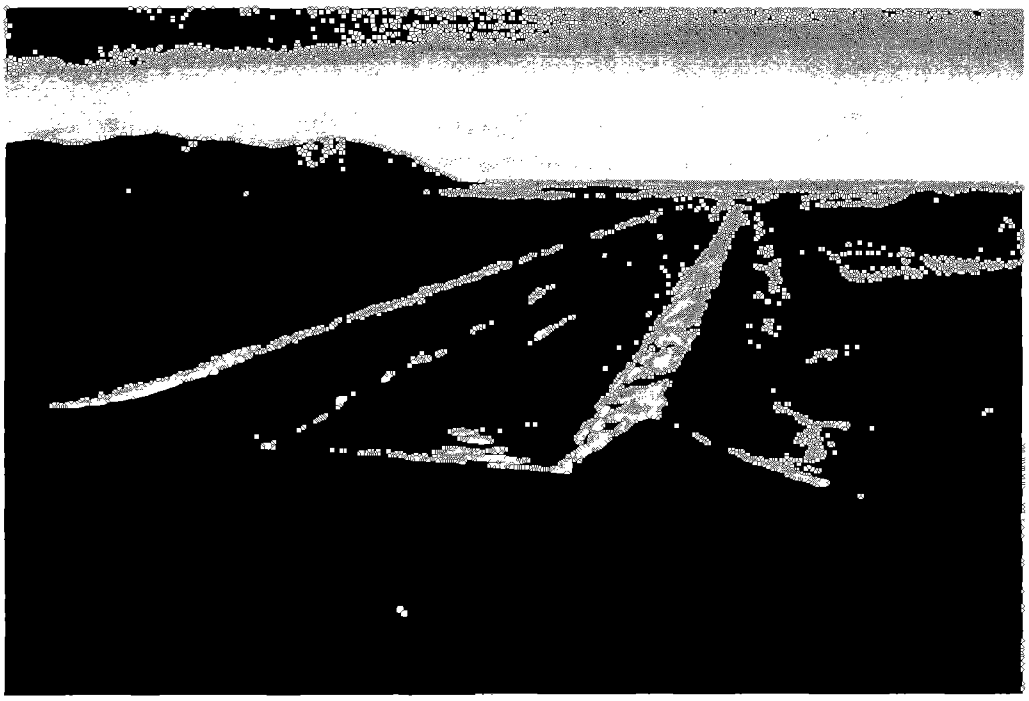


FIGURE 4

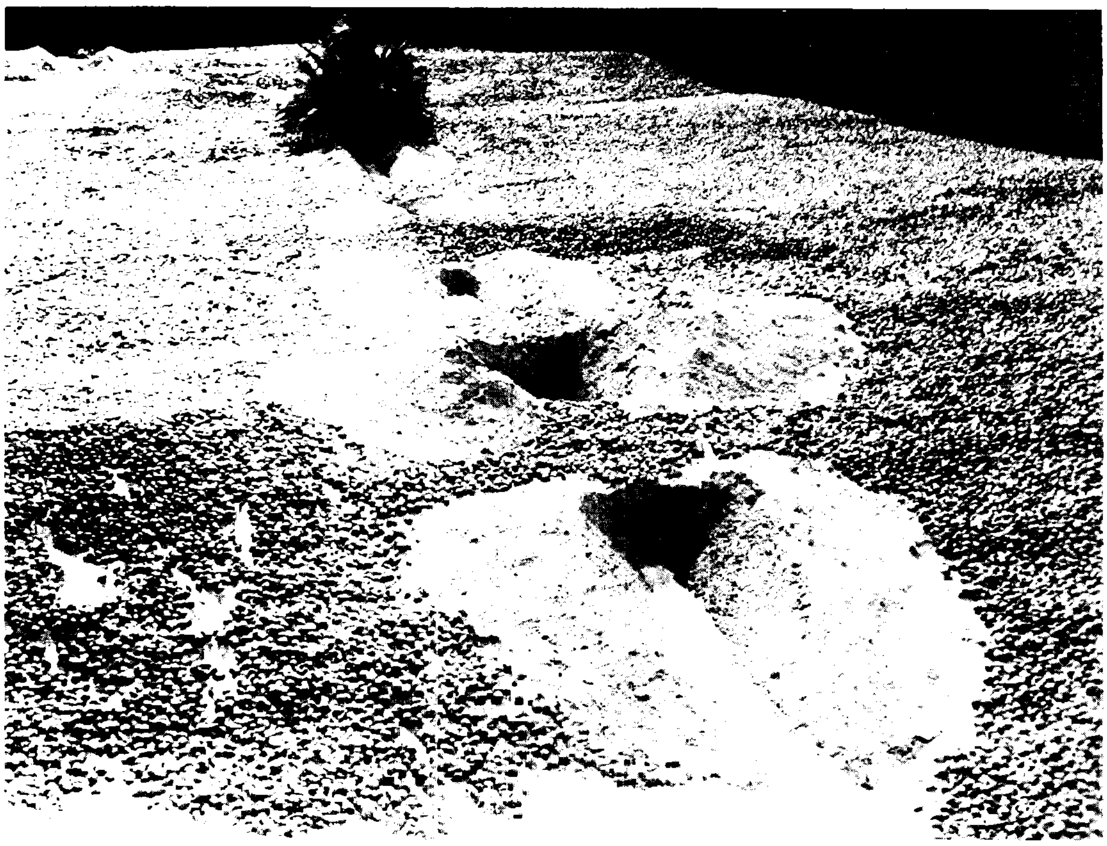


FIGURE 5

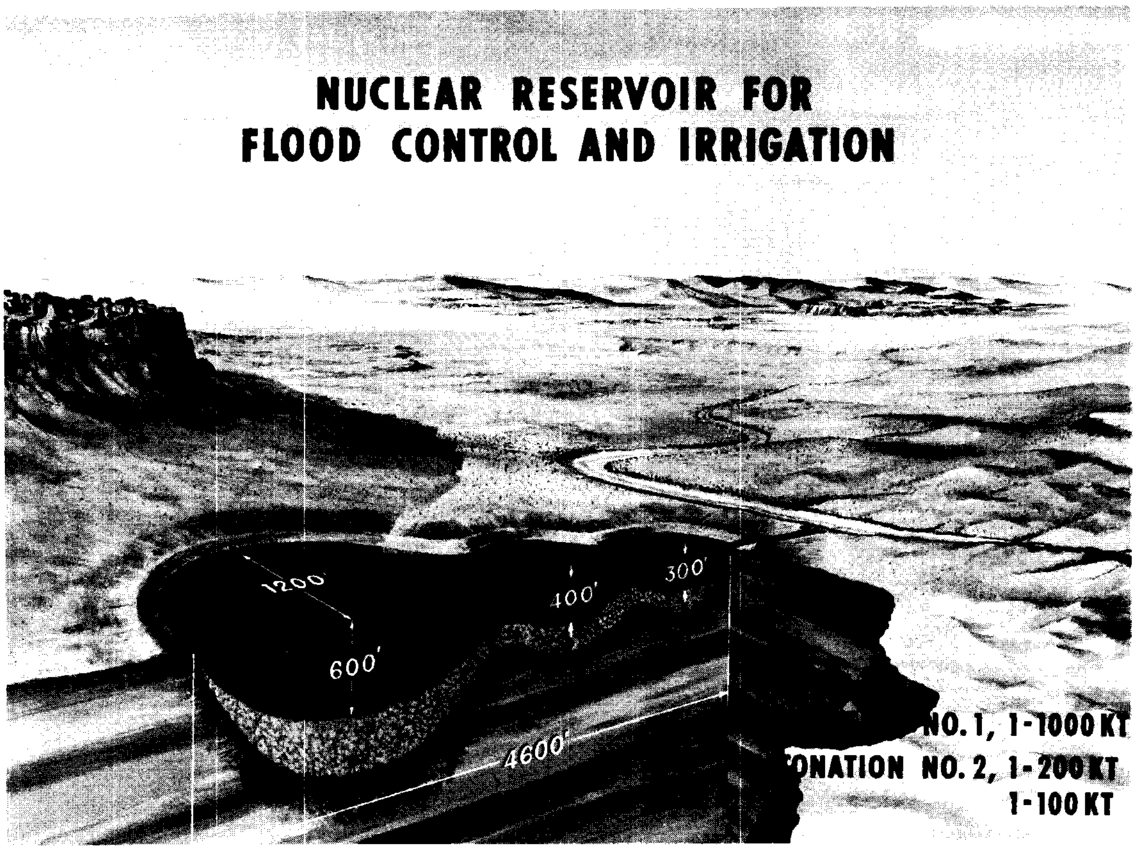


FIGURE 6

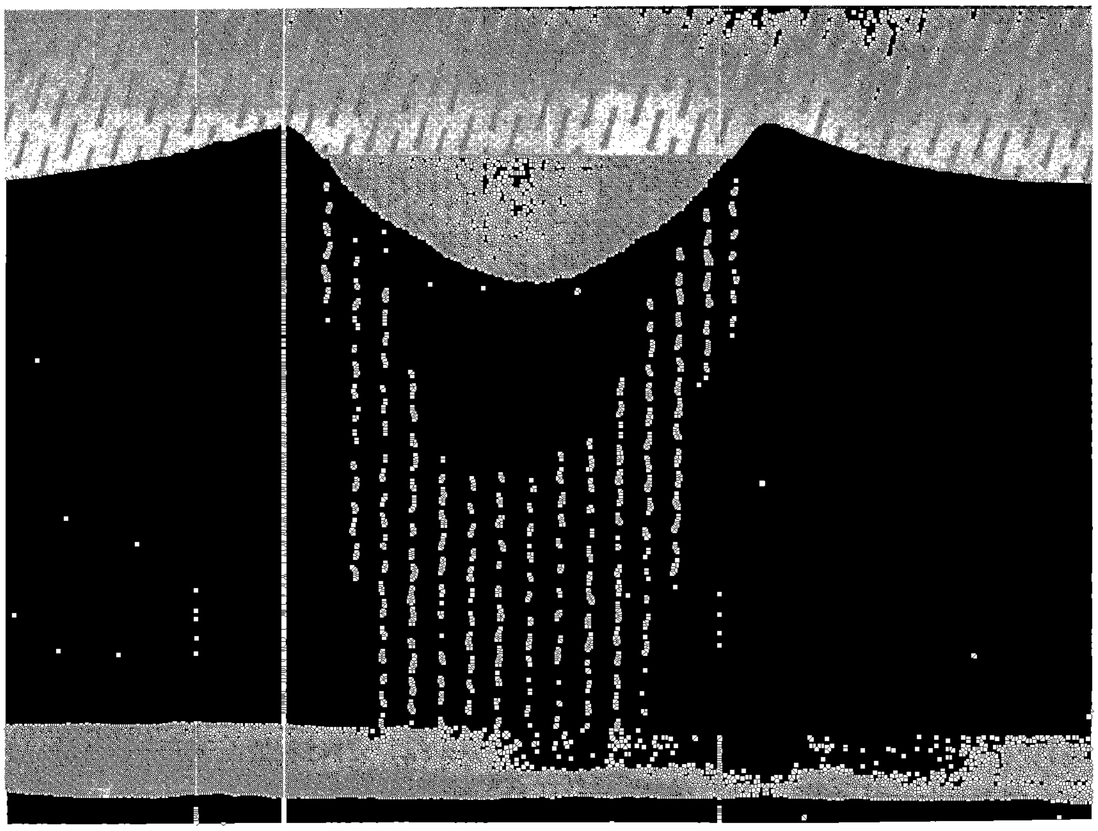


FIGURE 7

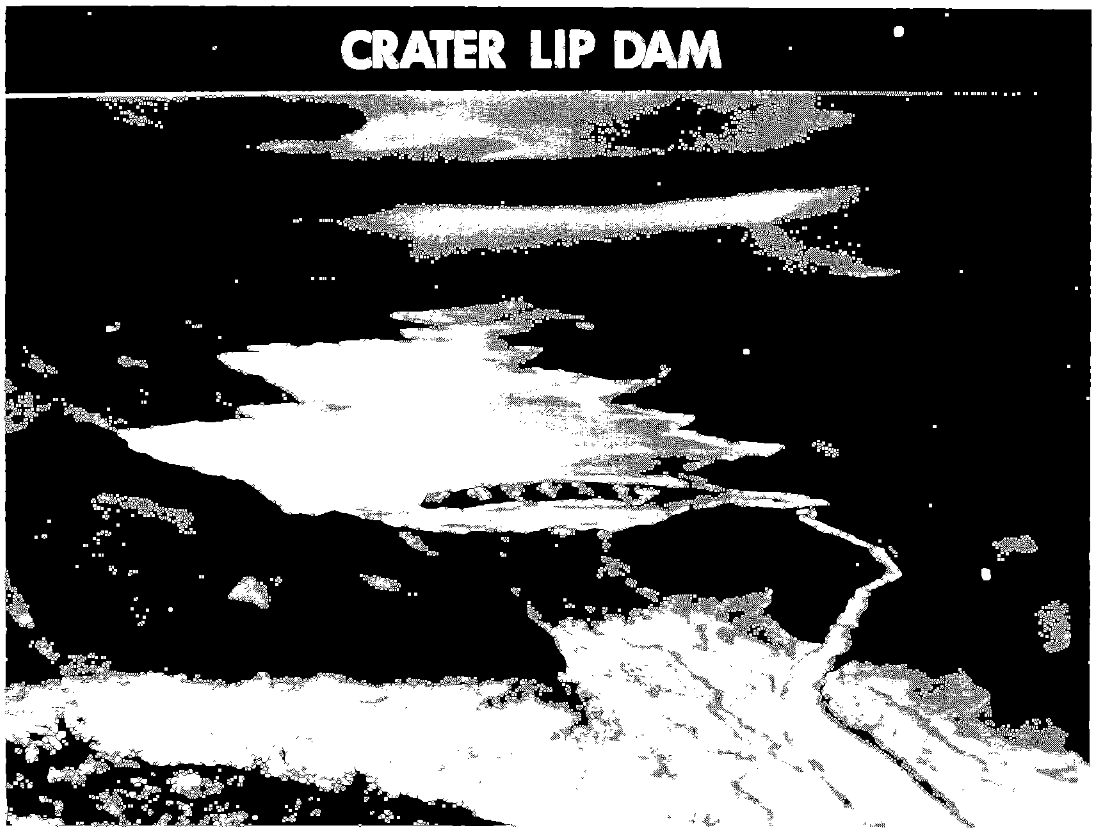


FIGURE 8

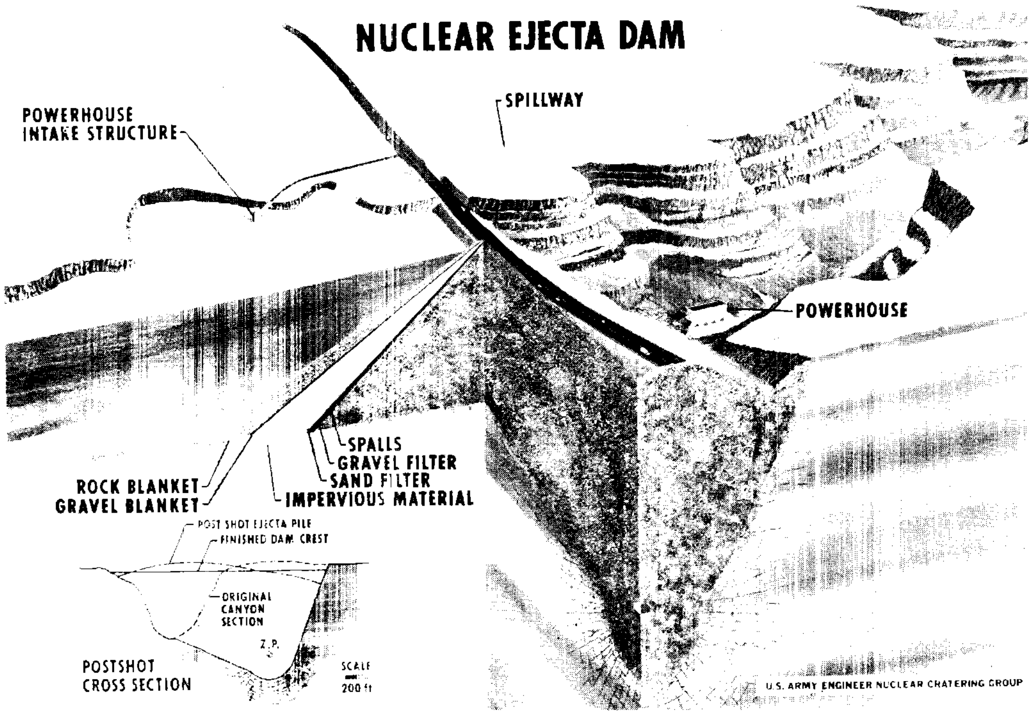


FIGURE 9

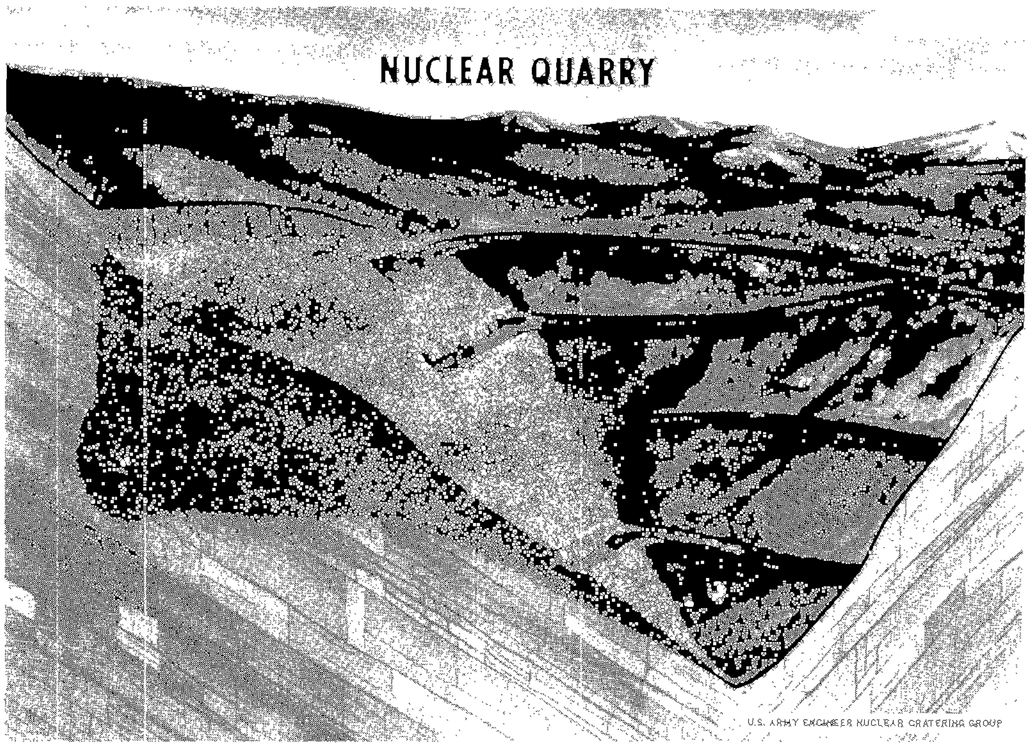


FIGURE 10

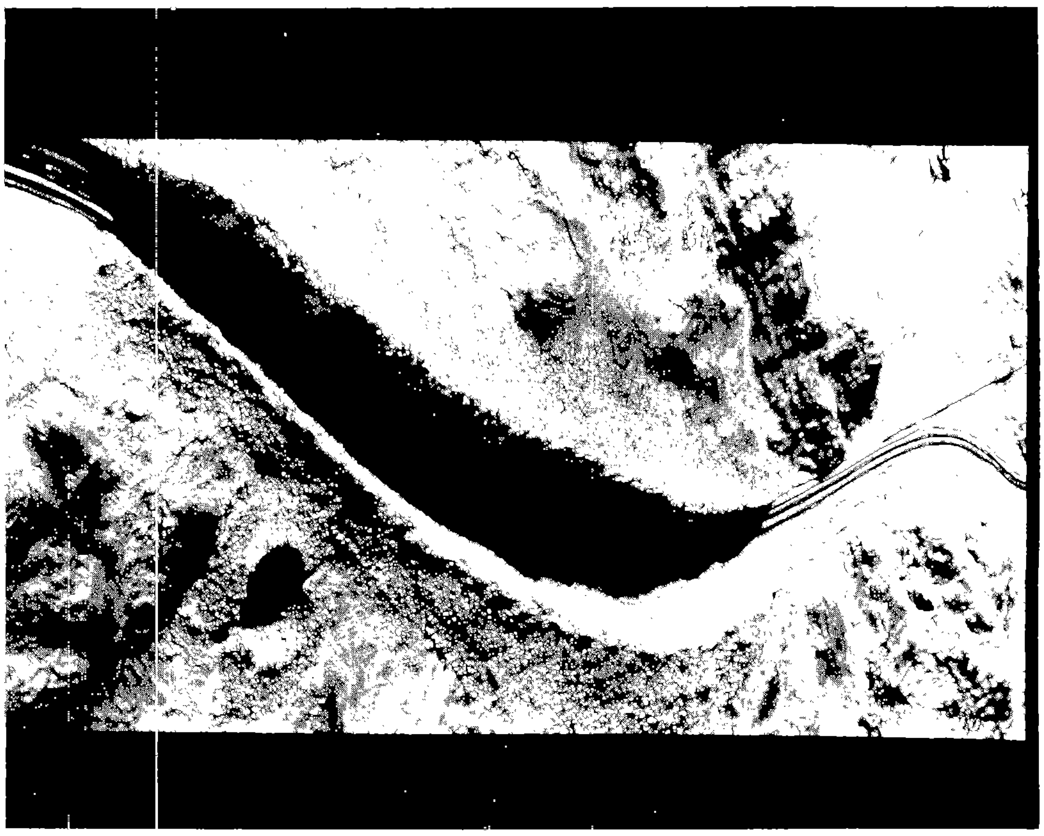


FIGURE 11

HARBOR EXCAVATION

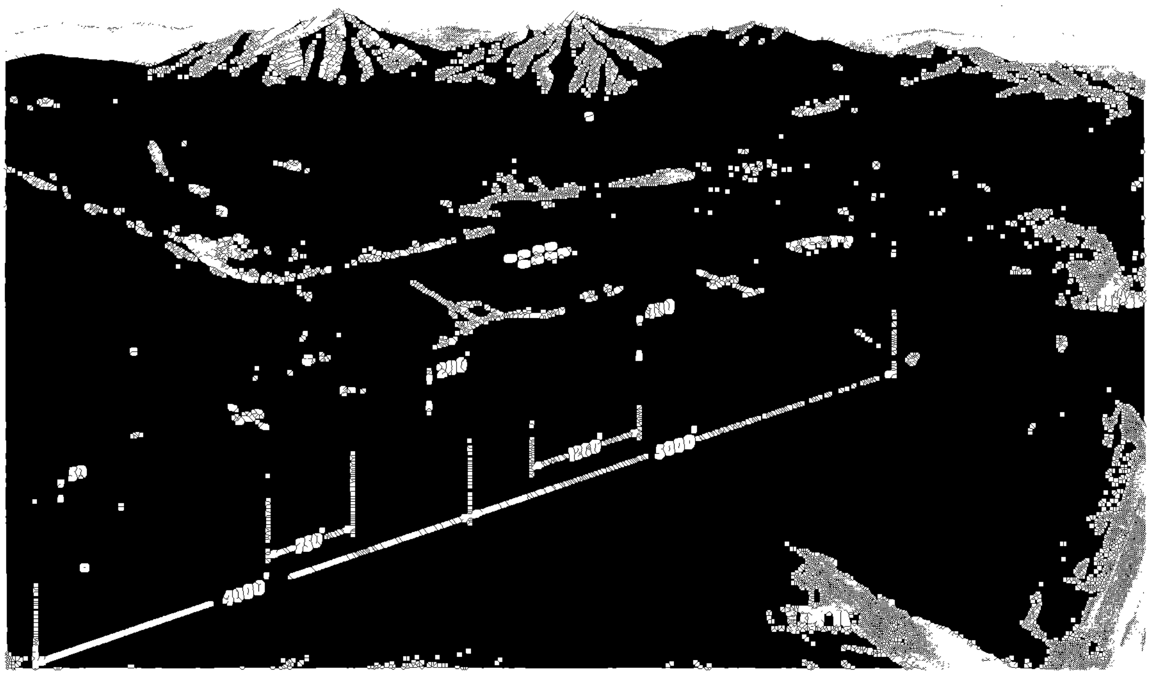


FIGURE 12

NUCLEAR HARBOR

CAPE KERAUDREN, WESTERN AUSTRALIA

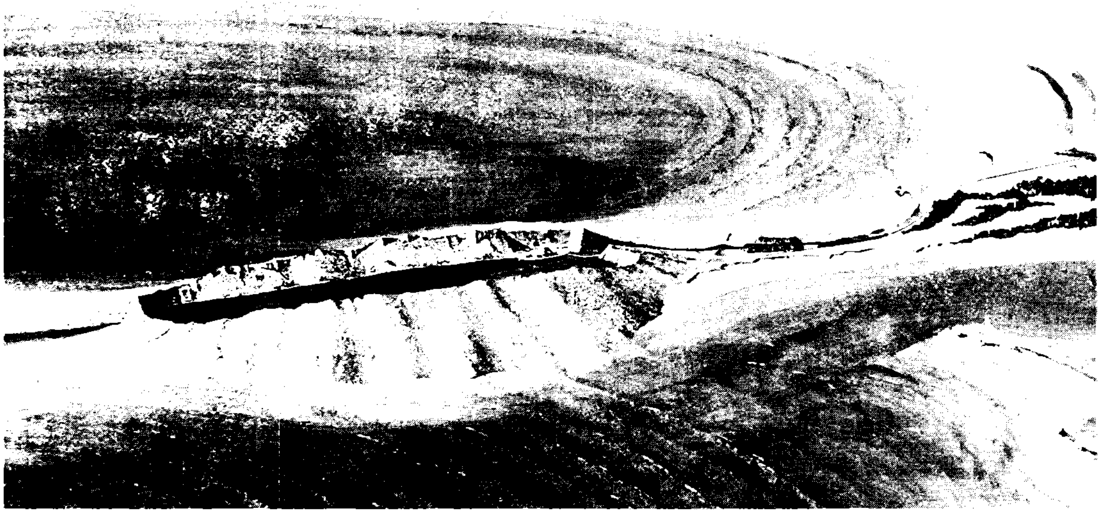
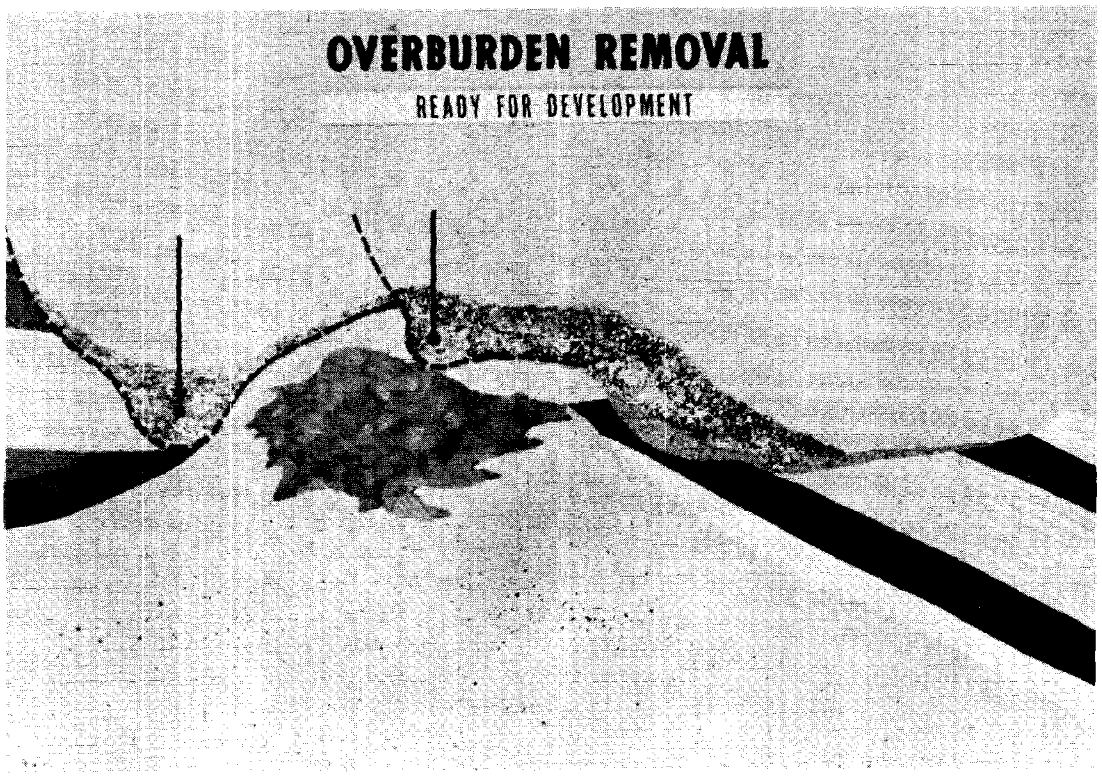


FIGURE 13



OVERBURDEN REMOVAL

READY FOR DEVELOPMENT

FIGURE 14

RETARCS FOR IN-SITU LEACHING

FIGURE 15

QUESTION FOR MARVIN M. WILLIAMSON

1. From R. C. Pendleton:

Conventional explosives leave no residual toxic materials. From the long-term contamination standpoint, can savings in dollars by using nuclear explosives be defended?

ANSWER:

The first thing we have to do is establish what the problem is as far as long-term contamination is concerned. As I noted when I started out, there are only two applications for excavation which are even in a feasibility study stage. There are no active projects for nuclear excavation. We are still in the development stage trying to find the answers. At this time I don't believe we can really say from a long-term contamination standpoint, I don't believe we have any comparison. We don't know how serious the problem might be or what it might cost to eliminate or reduce the problem.

SUMMARY OF RESULTS OF CRATERING EXPERIMENTS*

John Toman
Lawrence Radiation Laboratory
Livermore, California

ABSTRACT

The use of nuclear excavation as a construction technique for producing harbors, canals, highway cuts, and other large excavations requires a high assurance that the yield and depth of burst selected for the explosive will produce the desired configuration within an acceptable degree of tolerance.

Nuclear excavation technology advanced significantly during 1968 as a result of the successful execution of Projects Cabriolet, Buggy, and Schooner. Until these experiments were conducted, the only nuclear data available for designing large excavations were derived from Sedan (100 kt in alluvium), Danny Boy (0.42 kt in basalt), and Sulky (0.090 kt in basalt). Applicable experience has now been extended to include two additional rock types: tuff and porphyritic trachyte, non-homogeneous formations with severe geologic layering, and a nuclear row in hard rock. The continued development of cratering calculations using in situ geophysical measurements and high-pressure test data have provided a means for predicting the cratering characteristics of untested materials.

Chemical explosive cratering experiments conducted in the pre-Gondola series during the past several years have been directed toward determining the behavior of weak, wet clay shales. This material is important to nuclear excavation because of potential long-term stability problems which may affect the cratered slopes.

INTRODUCTION

Nuclear excavation as a construction technique for producing harbors, canals, highway cuts, and other large excavations requires a high assurance that the yield and depth of burst selected for the explosive will produce the desired configuration within an acceptable

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

degree of tolerance.

Nuclear excavation technology advanced significantly during 1968 as a result of the successful execution of Projects Cabriolet, Buggy, and Schooner. Until these experiments were conducted, the only nuclear data available for designing large excavations were derived from Sedan (100 kiloton [kt] in alluvium), Danny Boy (0.42 kt in basalt), and Sulky (0.090 kt in basalt). Applicable experience has now been extended to include two additional rock types: tuff and porphyritic trachyte, non-homogeneous formations with severe geologic layering, and a nuclear row in hard rock. The continued development of cratering calculations using in situ geophysical measurements and high-pressure test data have provided a means for predicting the cratering characteristics of untested materials.

Chemical explosive cratering experiments conducted in the pre-Gondola series during the past several years have been directed toward determining the behavior of weak, wet clay shales. This report will summarize all of the nuclear experiments of importance to the nuclear excavation program and a selected few chemical explosive (HE) experiments.

CRATERING PHENOMENOLOGY

Crater Formation

Maximum sized craters are formed at a depth of burst in which two predominant mechanisms combine to physically eject material above the explosive. These mechanisms are spall and gas acceleration or expansion of the cavity gases. Figure 1 shows pictorially the history of crater formation. The nuclear explosive on detonation creates tremendous pressures and temperatures which vaporize the rock out to a distance of approximately 2m(meters)/kt$^{1/3}$. At this point, a spherical pressure wave or shock wave separates from the fireball and propagates through the formation, melting, crushing, and fracturing the rock in sequence as it proceeds to the free surface. When the compressive wave reaches the free surface, a rarefaction wave is generated which propagates back toward the cavity. The rarefaction wave places the rock in tension, starting from the free surface. Since rock is weak in tension, it breaks and flies upward with a velocity that is related to the momentum imparted to it by the emerging compressive wave. This first motion is the spall mechanism. During the travel of the shock front to the free surface, the vaporized gases in the cavity have been expanding and enlarging the cavity. When the rarefaction wave reaches the spherically growing cavity, the cavity takes the path of least resistance and rapidly expands in the direction of the free surface. The rock above the cavity is recompacted and given additional velocity by the expanding cavity gases. This velocity increase over that due to spall is termed gas acceleration. Both of these phenomena can be measured in cratering experiments by high-speed photography of the ground surface. The ground surface assumes the shape of a dome and as it continues to grow, cracks open up through which the cavity gases may escape to the atmosphere and venting occurs. Upon general venting, the mound completely disintegrates, with the rock fragments given additional velocity and placed in ballistic trajectory. Material which excapes the crater is called ejecta and forms part of the crater lip. Other material falls back into the true crater to form the apparent crater. Apparent crater dimensions are referenced with respect to the original ground surface and represent the amount of useful excavation accomplished by the explosion. The crater lip projects above the original ground surface, and is composed of upthrust or permanently displaced rock and ejecta.

Figure 2 shows the mound growth of the Cabriolet experiment as a function of time. Figure 3 is an analysis of the surface velocity of the same mound (from high-speed photography) which clearly shows the spall and gas acceleration mechanisms.

Effects of Depth of Burst

The effect of increasing depth of burst on explosive phenomena is shown in Figure 4. For any explosive yield and medium, there is a depth of burst or a range of depths at which a maximum-sized crater will be formed. As the depth of burst is increased beyond that optimum depth, the craters become smaller until a mound of rubble, rather than a crater is formed. This rubble mound is called a "retarc." A maximum amount of rock is broken when a retarc is formed; it is ideally suited for utilization as a source of rock for aggregate. As the depth of burst is further increased, the explosive effects become contained. A cavity is formed by the explosion but there is no violent disruption of the free surface as in a cratering shot. The fractured rock above the cavity collapses into the cavity to form a chimney. Collapse continues out to the extent of the fracture radius where the rock may have sufficient strength to span the arch, or until the volume of the voids in the bulked chimney rock is equal to the original cavity volume. In alluvium and other materials which exhibit small increases or no increase of bulking on collapse, chimneying continues to the free surface and a collapse crater is formed. With no bulking, the volume of the collapse crater will be equal to the volume of the initial cavity. Changes in crater dimensions as a function of depth of burst are portrayed by cratering curves which are presented later.

Scaling

In order to use nuclear explosives as a construction tool, we must know crater sizes at explosive yields other than that for which experimental data are available. This is accomplished by determining the appropriate scaling law. Dimensional analysis indicates that crater volumes are proportional to the explosive yield and linear dimensions of the crater are proportional to the cube root of the explosive yield, if the effects of gravity are unimportant. This is cube-root scaling. Crater dimensions are increased by a factor of two for an eightfold increase in yield. Cube-root scaling adequately describes the performance of low-yield high-explosive charges (pounds to hundreds of pounds), but not at yields higher than about a ton. Crater dimensions in this yield range are better described as scaling by the 1/3.4 power of the yield. Simply stated, this means that yield must be increased by a factor of 10 to increase the linear dimensions of the crater by a factor of two. Dimensional analyses that include the effects of gravity indicate that for large yields at deep depths of burst, crater dimensions should scale as the fourth root of the explosive yield. Under this scaling law, explosive yields must be increased by a factor of 16 for a twofold increase in crater dimensions. No trend toward 1/4-root scaling has been observed in cratering experiments with yields as large as 100 kt, as seen in Figure 5. This is a plot of yield versus crater radius from applicable nuclear cratering experiments compared to calculated curves using the three scaling factors discussed briefly.

Effects of Rock Type

Differences in the physical properties of the material being cratered may play a more important role in estimating crater sizes for nuclear excavation than the scaling law used. The smallest scaled craters produced to date have been in hard, dry rock and the largest have been in wet, weak clay shales. Dimensions for craters in desert alluvium lie between the extremes for hard, dry rock and for weak clay shale. Non-homogeneous or layered formations are much more difficult to categorize and analyze. No high-explosives cratering series have been conducted to determine the effect of layering on crater dimensions. Three nuclear experiments (Cabriolet, Buggy, and Schooner), were conducted in layered media out of necessity. Of these three, only Buggy produced dimensions which were significantly smaller than those predicted on the basis of previous cratering experience in hard rock.

Effects of Explosive Types--Nuclear Explosives and High Explosives

Because of political and economic restraints, the bulk of cratering data are derived from high-explosives cratering experiments. Despite differences in the energy sources, cratering curves derived from high explosives define the nuclear curve sufficiently well to permit the design of nuclear cratering experiments for confirmation. A major shortcoming is that the optimum depth of burst for high explosives (HE) may occur at a scaled depth of burst which is larger than that for nuclear explosives (NE). This is most important in dry, hard rock where crater dimensions fall off very rapidly as the depth of burst is increased beyond the optimum and make crater size prediction in this range subject to greatest uncertainty. For a given yield of NE and HE at the same depth, the spall and gas acceleration velocities from an HE source are significantly larger than the velocities from an NE. This is shown most clearly in Figure 6[1], which compares surface velocities as a function of depth for both NE and HE. The HE curve is plotted mainly on the basis of 20-ton nitromethane charges in the pre-Schooner series. The separation of the NE and HE curves amounts to a factor of 3.75 times yield; i.e., if the 20 mass tons of HE were assumed to be about 75 energy tons, the HE and NE surface velocity curves would be virtually coincident. A comparison of scaled crater dimensions near optimum depth of burst does not support this NE-HE equivalence. It does indicate clearly, however, that if a velocity threshold between crater and retarc formation exists in hard, dry rock, it will occur at a much shallower scaled cube root depth of burst for NE.

RESULTS OF CRATERING EXPERIMENTS

General

An extensive amount of data has been developed and reported on explosive cratering in about the past 18 years. A summary of projects or events contributing to cratering technology with primary references is shown in Table I. This report will briefly discuss the most recent nuclear cratering experiments in hard rock and the HE experiments in a previously untested rock type, clay shale. In the nuclear excavation program to date, a total of seven nuclear cratering experiments have been conducted. These include Projects Sedan (100 kt), Danny Boy (0.42 kt), Sulky (0.09 kt), Palanquin (4.3 kt), Cabriolet (2.3 kt), Schooner (35 kt) and Buggy (row of 5 single 1.1 kt). The last three were conducted in 1968.

Description and Results of Single-Charge Craters--Nuclear

Sedan

The 100-kt Sedan explosive is the largest explosive charge detonated to date. It was buried at a depth of 193 m (635 ft) in desert alluvium and detonated on 6 July 1962. A crater with an apparent radius of 185 m (608 ft) and a depth of 98.5 m (323 ft) was produced. The apparent crater volume is about 5.1 × 10^6 m^3 (6.6 × 10^6 yd^3) and the lip volume 3.2 × 10^6 m^3 (4.2 × 10^6 yd^3). Crater lip heights range from 5.5 to 29 m (18 to 95 ft). In comparison to HE dimensions in the same material, the Sedan crater radius is approximately 10-20% smaller, but the depth is about the same when $W^{1/3.4}$ scaling is used.[11]

On detonation, a roughly hemispherical dome about 365 m (1200 ft) in diameter rose to a height of about 90 m (300 ft) in 3 seconds before the first venting was seen. The mound continued to rise until general venting and mound disintegration occurred at about 4.0 seconds. The dome height at this time was probably less than 200 m (660 ft). The initial spall velocities were on the order of 35 m/sec(115 ft/sec) and the late time velocities due to gas acceleration were over 40 m/sec(130 ft/sec). Figure 7 is a photograph of the Sedan crater.

Table I. Summary of projects or events contributing data for nuclear cratering technology (Nordyke).[2]

Project or event name	Date	No. of shots	Configuration	Explosive[a]	Approx. equiv. yields[b]	Depth of burst (ft)	Apparent crater radius (ft)	Apparent crater depth (ft)	Medium[c]	Ref.
Jangle S	1951	1	Single	NE	1.2 kt	3.5	45	21	Alluvium-10	3
Jangle U	1951	1	Single	NE	1.2 kt	17.0	130	53	Alluvium-10	3
Jangle HE	1951	10	Single	TNT	1.2-20 ton		Series		Alluvium-10	3
Teapot ESS	1955	1	Single	NE	1.2 kt	67.0	146	90	Alluvium-10	3
Mole, ERDL, SO	51/60	30	Single	TNT	0.13 ton		Series		Alluvium-10	3
Toboggan	59/60	92	Linear	TNT	—[d]		Series		Playa	4
Stagecoach	1960	3	Single	TNT	20 ton		Series		Alluvium-10	3,5
Scooter	1960	1	Single	TNT	500 ton	125	154	75	Alluvium-10	3,6
Buckboard	1960	13	Single	TNT	0.5-20 ton		Series		Basalt	7
Sandia, Alb.[e]	60/65		Row	TNT	—[e]		Series		Alluvium-Alb.	8
Rowboat	1961	8	Row	TNT	0.14 ton		Series		Alluvium-10	9
Danny Boy	1962	1	Single	NE	0.42 kt	110	107	62	Basalt	10
Sedan	1962	1	Single	NE	100 kt	635	608	323	Alluvium-10	11
Pre-Buggy I	1962	18	Row	NM	0.5 ton		Series		Alluvium-5	12
Pre-Buggy II	1963	10	Row	NM	0.5 ton		Series		Alluvium-5	13
Pre-Schooner I	1964	4	Single	NM	20 ton		Series		Basalt	14
Dugout	1964	1	Row	NM	20 ton	59 (spacing: 45)	width: 136	35	Basalt	15
Sulky	1964	1	Single	NE	87 ton	90	—	—	Basalt	16
Palanquin	1965	1	Single	NE	4.3 kt	280	119	78.8	Rhyolite	17
Pre-Schooner III	1965	1	Single	NM	85 ton	71	95	61	Rhyolite	18
Pre-Gondola I	1966	4	Single	NM	20 ton		Series		Saturated shale	19
Pre-Gondola II	1967	1	Row	NM	20-40 ton	50-60 spacing: 80	—	—	Saturated shale	20
Cabriolet	1968	1	Single	NE	2.6 kt	170.75	178	120	Rhyolite	21
Buggy	1968	5	Row	NE	1.1 kt	135.0 spacing: 150	width: 254	69.8	Basalt	1
Pre-Gondola III	1968	7	Row	NM	30 ton	spacing: 50-56	width: 187-214	50-53	Saturated shale	20
Schooner	1968	1	Single	NE	35 kt	355	426	208	Tuff	2

[a] NE, nuclear explosives; TNT, conventional high explosives; NM, liquid nitromethane.

[b] For 1 kt, equivalent yield = 10^{12} cal.

[c] Alluvium-10: Desert alluvium, Area 10, NTS.
Alluvium-5: Desert alluvium, Area 5, NTS.
Alluvium-Alb.: Desert alluvium, Albuquerque, New Mexico.
Playa: Yucca Lake, NTS.
Basalt: Buckboard Mesa, NTS.
Rhyolite: Schooner Site, Bruneau River Plateau, Idaho.
Saturated shale: Fort Peck, Montana.

[d] Toboggan line charges ranged from 0.23 to 42.7 lb/ft.

[e] Since 1960, Sandia Corporation has conducted a continuing small-scale cratering program at Albuquerque, to investigate various problems related to rows and arrays of charges.

Danny Boy

Project Danny Boy, the first nuclear excavation experiment conducted in dry, hard rock, consisted of a 0.42-kt explosive detonated at a depth of 33.5 m (110 ft) on 5 March 1962. The rock is simply described as a gray, dense, nonvesicular basalt with a density of 2.6 g/cm^3. The resultant crater has a radius of 33 m (107 ft) and a depth of 19 m (62 ft). The volume of the apparent crater is about 27,500 m^3 (36,000 yd^3) and the lip volume 61,000 m^3 (80,000 yd^3), of which 42,750 m^3 (56,000 yd^3) is ejecta. A major portion of the lip height, which averages 7.3 m (24 ft), is caused by upthrust. Ejecta on the lip ranges from 2 to 10 feet with an average depth of 5 feet.[22] Within the normal scatter of data, the Danny Boy scaled dimensions are essentially identical to those produced by high explosives at this depth of burst.

On detonation, the ground moved at a fairly constant velocity of about 42 m/sec (138 ft/sec).[23] By 1.6 seconds, the dome had a diameter of about 250 feet and a height of 200 feet. No venting of hot gases was ever seen and the mound disintegrated at about 4 seconds with the ejected material in a free fall status. The initial spall velocities were so high that a distinct gas acceleration phase was not obvious. A slight increase in surface velocity to about 47 m/sec at late times can be interpreted from the meager surface velocity data available, but the main impact of the expanding cavity gases was to sustain the initial spall velocities over a long period of time. Until 1968, Danny Boy provided the only basis for predicting nuclear crater sizes in hard rock. A photograph of the Danny Boy crater is shown in Figure 8.

Sulky

Project Sulky was designed to investigate the nature of the nuclear cratering curve at a scaled depth greater than optimum. A 0.09-kt explosive was detonated on 18 December 1964, at a depth of 27.4 m (90 ft) in the same basalt formation as Danny Boy. Although high explosives at this scaled depth of burst would have produced a crater, Sulky resulted in a rubble mound or retarc. Sulky was a valuable experiment in that it established a sharp break in the nuclear cratering curves beyond scaled depths of burst greater than about 40 m/kt$^{1/3.4}$, or 140 ft/kt$^{1/3.4}$, and provided information on the rock-breaking capabilities of nuclear explosives for quarrying applications.

On detonation, the surface mounded in the typical manner, but the initial spall velocity of 85 ft/sec[24] without an ensuing gas acceleration was insufficient to eject material to form a crater. Surface layers of rock reached a maximum height of about 100 feet and landed within an average radius of 24 m (79 ft)[16] from surface ground zero. The lip or mound height averages 6.3 m (21 ft),[16] and the mound volume is approximately 11,700 yd^3. The Sulky retarc is shown in Figure 9.

Palanquin

Project Palanquin was executed on 14 April 1965 in a dense, dry rock identified as porphyritic trachyte. An explosive with a yield of 4.3 kt was buried at a depth of 85.3 m (280 ft) to produce a retarc for further study of quarrying applications. However, a stemming failure of the emplacement hole resulted in the very early venting of hot cavity gases and an erosional crater was produced. The mechanisms forming such a crater are vastly different from the mechanics associated with normal crater formation. Therefore, the crater dimensions from Palanquin are not considered valid for comparative purposes and are not plotted as cratering data. For general information,[25] the resultant crater has a radius of 36 m (119 ft), a depth of 24 m (79 ft), and a lip height of 6.5 m (21 ft). The apparent crater has a volume of 35,800 m^3 (46,800 yd^3), and the lip volume is 100,000 m^3 (131,300 yd^3). Potential applications may be found in which the gas-erosional mechanism may be useful. Figure 10 is a photograph of the Palanquin crater. Shown on the crater lip is the casing used in the emplacement hole, which is believed to be responsible for the early venting.

Cabriolet

The Cabriolet explosive (yield about 2.3 kt) was detonated on 26 January 1968 at a depth of 52 m (170 ft)[21] in a dense, dry porphyritic trachyte rock, similar to that at the Palanquin site. A crater was produced with an apparent radius of 55 m (181 ft), a depth of 36 m (117 ft), a lip height of 9.4 m (31 ft), and an ejecta boundary radius of 202 m (662 ft). The apparent crater volume is 137,645 m^3 (180,000 yd^3) and the lip volume, 184,940 m^3 (241,890 yd^3). The scaled dimensions of Cabriolet are only slightly larger than Danny Boy in radius (142 $ft/kt^{1/3.4}$ vs 139 $ft/kt^{1/3.4}$), but significantly deeper in depth (92 $ft/kt^{1/3.4}$ vs 80 $ft/kt^{1/3.4}$). The Cabriolet scaled depth of burst was smaller than that for Danny Boy (133 $ft/kt^{1/3.4}$ vs 142 $ft/kt^{1/3.4}$).

Upon detonation, the ground surface mounded in a normal manner with venting of hot gases occurring near the center of the mound at 775 msec. The dome was about 25 m (80 ft) above the ground surface elevation at this time. Upon general venting at 1 second, material was ejected to a maximum height of about 460 m (1500 ft) above the terrain.[21] Ground surface velocities were lower than would have been predicted on the basis of data from Danny Boy and Sulky. This appears to result from the fact that the rock formation at the Cabriolet site was layered with lower-density rock ($\sim$2.15 g/cc) existing to a depth of about 30 m (98 ft) and higher density rock ($\sim$2.5 g/cc) extending from 30 m to the shot point. The initial spall velocity of 30 m/sec is smaller than the 42 m/sec seen on Danny Boy, but the definite gas acceleration phase of Cabriolet increased the final velocity to about 45 m/sec (see Figure 6). In a homogeneous hard rock like Buckboard basalt, the Cabriolet spall velocity should have been about 50 m/sec or 70% higher. Figure 11 is a photograph of the Cabriolet crater.

Schooner

The Schooner experiment, with an explosive of 35 ± 5 kt placed at a depth of 355 feet in a tuff formation, was executed on 8 December 1968. A primary purpose of the experiment was to determine the effect of yield escalation on crater size in hard rock. The Schooner explosive yield was about 15 times larger than the Cabriolet yield. Preliminary measurements of the Schooner crater provide the following average results:[26]

Apparent radius	130 m	426 ft
Apparent depth	63.4 m	208 ft
Apparent lip height	13.4 m	44 ft
Lip crest radius	147 m	483 ft
Radius of ejecta boundary	538 m	1768 ft
Apparent crater volume	1.74×10^6 m^3	2.28×10^6 yd^3
Apparent lip volume	2.1×10^6 m^3	2.75×10^6 yd^3

The Schooner scaled crater radius is significantly larger than that of Cabriolet or Danny Boy (150 ft/kt$^{1/3.4}$ vs 142 and 139 ft/kt$^{1/3.4}$), but the scaled depth is less (73 ft/kt$^{1/3.4}$ vs 92 and 80 ft/kt$^{1/3.4}$).

On detonation,[27] a peak spall velocity of 55 m/sec (180 fps) was measured at about 200 msec. A gas acceleration phase increased the velocity to about 65 m/sec (215 fps), starting at 600-700 msec. The mound reached a height of 83 m (270 ft) at 1.73 seconds before obscuring the surface motion flares. First venting of the dome occurred at 1.75 seconds. At about 2.0 seconds, the mound erupted violently, ejecting missiles out to ranges greater than one mile.

The shallow scaled crater depth does not appear to be consistent with the high mound velocities measured. A plausible explanation stems from the nature of the geologic structure at the site, which had the net effect of turning the velocity vectors toward SGZ as much as 15 degrees away from a radial direction through the shot point.[28] This effect may have caused more material to fall within the crater boundary as fallback. The velocity vectors on Cabriolet were essentially radial from the shot point.

The geologic structure at the Schooner site is such that it can be divided into four primary layers.[29] The first layer extending from the surface to 120 ft is a dry, dense competent welded tuff with an average density of 2.353 g/cc. The second layer extending to 210 feet is very porous, with a dry density of 1.5 g/cc and an average water content of 8-10% by weight. The third, from 210 to 337 feet, is extremely porous, with a dry density of 1.25 g/cc and 20-38% water by weight. The fourth layer, from 337 to 480 feet is similar to the first. In the photograph of the Schooner crater (Figure 12) the hard, competent first rock layer is seen exposed in the upper part of the cratered slope.

HE Explosives Craters in Clay Shale

Because of the need to explore the cratering characteristics of a weak, wet-clay shale, the U. S. Army Engineer Nuclear Cratering Group initiated a series of high-explosives cratering experiments in 1966, called Project pre-Gondola.[19] The experiments are being conducted near Fort Peck, Montana, where the physical properties of the Bear Paw Shale closely resemble those of the Sabana Shale of Panama, which occurs along 19 miles of a proposed 50-mile route across the Isthmus of Panama, for a sea-level canal. In the pre-Gondola I series, four 20-ton charges of high explosives [nitromethane (NM)] were detonated at varying depths of burst to define the cratering curves. A surprising result was that the scaled dimensions of the pre-Gondola craters are much larger than those in hard rock or alluvium. Mound velocities, however, are almost identical to those obtained for a similar series of experiments, pre-Schooner I, in the Buckboard basalt.[19] A major factor contributing to large crater size in the shale when compared to basalt is the significant difference in unconfined compressive strengths of the rocks--less than 500 lb/in.^{2} for shale[19] to about 20,000 lb/in.^{2} for dense, dry basalt.[30] Unweathered shale has an average *in situ* wet density of 2.08 g/cc and a dry density of 1.74 g/cc, indicating about 20% water by weight.[19] The crater profiles in shale are also quite different from those in hard rock or alluvium. The average crater slopes in shales are about 26 degrees while those in hard rock and alluvium are 35 to 37 degrees or much steeper. Actual dimensions of the pre-Gondola I craters[19] are:

Event	Charge weight (ton)	Depth of burst		Apparent radius		Apparent depth	
		(ft)	(m)	(ft)	(m)	(ft)	(m)
Charlie	19.6	42.5	12.9	80	24.5	33	10
Bravo	19.4	46.2	14.1	79	23.9	30	9
Alfa	20.4	52.7	16.1	76	23.2	32	9.8
Delta	20.2	56.9	17.3	65	19.8	25	7.7

Comparison of Cratering Curves

The cratering curves for radius and depth shown in Figure 13a and 13b compare the dimensions of all single craters summarized here by $W^{1/3.4}$ scaling. For scaling purposes, it has been assumed that 0.78 mass tons of NM = 1.00 mass tons of TNT[31] = 1.0 energy ton nuclear = 10^9 calories. If the ratio of the heats of detonation of NM and TNT is the only factor used as the basis for a NM-TNT energy equivalence, then 0.9 mass tons of NM = 1.00 mass tons of TNT. This equivalence will increase both the scaled dimensions and the depth of burst for the NM experiments plotted.

ROW CRATER EXPERIENCE

Background

Most nuclear excavation applications involve the simultaneous detonation of multiple explosives placed in a row to form a linear channel, rather than a circular crater. Many small-scale row cratering experiments such as pre-Buggy I and II[12,13] with charge weights up to 1,000 lb have been conducted in alluvium. The purpose of row-cratering experiments is generally to determine the effect of variation of spacing on row-crater parameters. In general, the results from experiments in alluvium indicate that:

1. Spacing between explosives of one single-charge crater radius will produce a row with a half-width approximately 10 to 20% larger than the single crater radius.
2. A spacing of about 1.25 times a single crater radius produces a row with dimensions approximately equal to that of a single charge.
3. The lips on the sides of a row crater are 50 to 100% higher than the lip of a single crater, but the lip heights off the row ends are very small.

Row-charge cratering experience in hard rock is limited to two experiments, Dugout (HE) and Buggy (NE). On the basis of these results, it would appear that the conclusions drawn for row cratering in alluvium will be somewhat similar for hard rock.

Dugout

In June 1964, the Dugout experiment was conducted in basalt on the Buckboard Mesa, NTS. Five spheres containing 20 tons of nitromethane (HE) were detonated simultaneously. The depth of burst was 59 feet and the spacing 45 feet between charges. Average dimensions of the linear portion of the crater are shown below.[15]

Half width $\left(\frac{W_a}{2}\right)$	20.8 m	68.4 ft
Apparent depth	10.7 m	35.1 ft
Apparent lip height (sides)	7.2 m	23.6 ft
Apparent lip height (ends)	3.0 m	9.9 ft
Apparent crater volume	16.1×10^3 m^3	21×10^3 yd^3

A significant result of the Dugout experiment was that the volume excavated per unit charge is 50% greater than the maximum volume attainable with a single charge. A volume of 2145 m^3 was the maximum volume of a single 20-ton NM crater (pre-Schooner Alfa) on Buckboard Mesa.[14] The linear dimensions of the Dugout crater are approximately equal to the dimensions expected from 60-ton charges

(3 times the Dugout yield) near an optimum depth of burst and at a spacing which produces no enhancement over the single charge. Linear dimensions of Dugout are shown to scale on the cratering curves in Figure 13. The charge spacing in the Dugout experiment was much closer than had been tried in the alluvium row crater experiments when spacing is defined relative to the depth of burst rather than to a single crater radius. A close spacing concept of row charges (where spacing <1.0 depth of burst), as typified by Dugout (spacing = 0.76 feet depth of burst) is of particular importance in nuclear excavation. When the total salvo yield is restricted due to seismic limitations, the close spacing concept makes it possible to significantly reduce the salvo yield without reducing the channel cross section. Reduction in salvo yield must be balanced against the higher cost of a greater number of emplacement holes and explosives for the same channel length. Another possible advantage of close spacing is that one nuclear explosive yield can be made to look like a family of yields. As the charges are brought closer together, the increased yield per unit length requires that the charges be buried deeper to remain at the optimum of the single-charge cratering curves. A number of experiments would be needed to define the proper spacing and depth of burst to optimize the volume excavated per unit charge. In general, the depths of burst will be greater than those which are optimum for the single charge, and depending on the enhancement desired, may be at retarc or greater depth of burst for the individual charge. Simple vector addition of the mound velocities from adjacent charges can be used to gain insight into the proper spacing and depth required to produce a specified surface velocity, but unfortunately, peak surface velocities do not relate directly to crater dimensions.

A photograph of the Dugout crater is shown in Figure 14.

Buggy

Project Buggy,[1] the first nuclear row-excavation experiment, was an important experiment in that it confirmed the basic concepts of channel excavation derived from HE experiments at very low yields, and proved the value of theoretical cratering calculations in predicting the effects of a nuclear detonation in an untested environment. Five nuclear explosives, each with a yield of 1.1 kilotons, were detonated simultaneously on 12 March 1968 in a dry, complex basalt formation on Chukar Mesa, NTS. The explosives were buried at a depth of 41.1 m (135 ft) and spaced 45.7 m (150 ft) apart. A photograph of the Buggy crater is shown in Figure 15. The excavated channel has the following average dimensions:

Apparent crater width	77.4 m	254 ft
Apparent crater depth	19.8 m	65 ft
Apparent crater length	260.6 m	855 ft
Apparent lip height (sides)	12.4 m	41 ft
Apparent lip height (ends)	4.37 m	14 ft
Lip crest width	108 m	355 ft

Apparent crater volume	200,607 m^3	262,456 yd^3
Apparent lip volume	322,811 m^3	422,205 yd^3

The apparent dimensions are significantly smaller than those which would be predicted on the basis of Danny Boy dimensions in the Buckboard basalt (radius 10% less; depth 19% less). It is believed that the small crater dimensions are due largely to the geologic conditions existing at the Buggy site. Differences in the cratering characteristics of the two basalt formations were determined by cratering calculations (TENSOR code)[32] after the depth of burst and spacing were selected by scaling Danny Boy dimensions. Initially, a depth and spacing of 150 feet were chosen to represent optimum depth of burst and 1.0 radius or 1.0 depth-of-burst spacing. The calculations indicated that the 150 feet depth of burst was too deep to form an ejecta crater for a single Buggy explosive. The depth was reduced to 135 feet to insure crater formation, but the emplacement holes had been constructed and the spacing could not be altered. This circumstance, fortuitously, led to the finding that spacings between about 1.15 and 1.25 radii (or 1.1 depth of burst) can produce channels in hard rock, free of noticeable scalloping or severe irregularities. Since no previous experiments had been conducted on Chukar Mesa, the actual radius spacing was determined from the average radius at both ends of the Buggy row. Geologic conditions at the Buggy site varied from one end of the row to the other. Layers of basalt with different densities and compressional velocities with resultant impedance mismatch between layers distinguished the formation. A dominant feature was a competent, dense, high velocity layer with extended over three charges (A, B, and C) from a depth of about 30 to 90 feet.

The surface velocities measured on detonation were in good agreement with those calculated for a single charge. Initial spall velocities ranged from about 24 to 35 m/sec (79 to 115 ft/sec), depending on location along the line of charges. A gas acceleration phase increased these velocities along the entire mound to a peak of 45 m/sec (148 ft/sec) over Charge B. In the fairly homogeneous Buckboard basalt at the Buggy scaled depth of burst, the spall velocity would be expected to be about 50 m/sec (164 ft/sec) and the total peak velocity about 60 m/sec (200 ft/sec). Figure 16 shows preliminary surface motion data for Buggy along the longitudinal axis.

CONCLUSIONS

Nuclear excavation technology has taken a great stride forward as a result of a better understanding of the changes generated in the cratering process by layered rock formations, such as those encountered in the Buggy, Cabriolet, and Schooner experiments. Preshot insight into the nature of these changes was made possible by the use of cratering code calculations which use in situ and laboratory test data on rock samples of the formation. Nuclear excavation projects in untested formations can now be designed with a greater assurance that the depth of burst and yield can be specified to provide the desired structure. For nuclear excavation experiments conducted to date through the 100-kt level, no trend toward 1/4 root scaling has been observed. A comparison of cratering data in three different materials (dry rock, alluvium, and shale) indicates that differences in physical properties affect crater dimensions more significantly than possible differences in yield scaling exponents. The rather small-scaled dimensions observed in the Buggy row-crater experiment should not be considered typical for large nuclear excavation projects. The presence of water at the shot point and in overlying formations, which is likely to be encountered in most locations away from the Nevada Test Site, is expected to significantly increase the cratering efficiency of nuclear explosives.

REFERENCES

1. Toman, J., Project Buggy: A Nuclear Row Excavation Experiment, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-71280 (1968).

2. Nordyke, M. D., Lawrence Radiation Laboratory, Livermore, private communication (1969).

3. Nordyke, M. D., "An Analysis of Cratering Data from Desert Alluvium," J. Geo. Res. 67, 1965 (1961).

4. Carlson, R. H., "High Explosive Ditching from Linear Charges," J. Geo. Res. 68, 3693 (1963).

5. Vortman, L. J. et al., Project Stagecoach, Final Report, Sandia Corp. SC-4596(RR) 1960.

6. Perret, W. R. et al., Project Scooter, Final Report, Sandia Corp. Rept. SC-4602(RR) 1963.

7. Vortman, L. J. et al., Project Buckboard, Final Report, Sandia Corp. Rept. SC-4675(RR) 1962.

8. Vortman, L. J. and Schofield, L. M., The Effect of Row Charge Spacing and Depth on Crater Dimensions, Sandia Corp. Rept. SC-4730(RR) 1963.

9. Myers, B., Summary Report--Project Rowboat, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-12118 (October 5, 1964).

10. Nordyke, M.D. and W. R. Wray, "A Nuclear Cratering Detonation in Basalt," J. Geophys. Res. 69, 675-690 (1964).

11. Nordyke, M.D. and M. M. Williamson, The Sedan Event, Lawrence Radiation Laboratory, Livermore, Rept. PNE-242F (April 1965).

12. Graves, E., W. Wray, and R. Pierce, Scope of Chemical Explosive Cratering Experiment, Pre-Buggy, Preliminary Rept., U. S. Army Corps of Engineers Nuclear Cratering Group, Rept. PNE-300 (1963).

13. Spruill, J. L. and F. F. Videon, Project Pre-Buggy II. Studies of the Pre-Buggy II Apparent Craters, U. S. Army Engineer Nuclear Cratering Group, Livermore, Rept. PNE-315F (June 1965).

14. Spruill, J. L. and R. A. Paul, Project Pre-Schooner--Crater Measurements, U. S. Army Engineer Nuclear Cratering Group, Livermore, Rept. PNE-502F (March 1965).

15. Spruill, J. L., Project Dugout--Apparent Crater Studies, U. S. Army Nuclear Cratering Group, Livermore, Rept. PNE-601F (March 1965).

16. Videon, F. F., Project Sulky--Crater Measurements, U. S. Army Engineer Nuclear Cratering Group, Livermore, Rept. PNE-713F (October 1965).

17. Videon, F. F., Project Palanquin--Studies of the Apparent Crater, U. S. Army Engineers Nuclear Cratering Group, Rept. PNE-904 (July 1966).

18. Benfer, Maj. R. H., Project Pre-Schooner II--Apparent Crater Studies, U. S. Army Engineer Nuclear Cratering Group, Livermore, Rept. PNE-508F (November 1966).

19. Kurtz, Lt. Col. M. M., Project Pre-Gondola I, Technical Director's Summary Report, U. S. Army Engineers Nuclear Cratering Group, Livermore, Rept. PNE-1102 (May 1966).

20. Kurtz, M. K., Jr., A Report on the Scope and Preliminary Results of Project Pre-Gondola II, U. S. Army Engineers Nuclear Cratering Group, Rept. NCG/TM 67-9 (August 1967).

21. Tewes, H. A., *Results of the Cabriolet Excavation Experiment*, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-71196 (1968).

22. Leisek, J. F., Postshot Geologic Investigations of the Danny Boy Nuclear Cratering Experiment in Basalt, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-7803 (1964).

23. Carder, B. M. et al., Project Danny Boy, Surface Phenomena Photography, EG&G, Inc., Rept. POIR-1812 (Feb. 1963).

24. Brower, R. and D. Wilson, Project Sulky *Scientific Photography*, EG&G, Inc., Rept. PNE-710F (Nov. 1966).

25. Videon, F. F., Project Palanquin: Studies of the Apparent Crater, U. S. Army Engineers Nuclear Cratering Group, Livermore, Rept. PNE-904 (July 1966).

26. Redpath, B.--private communication.

27. Rohrer, R.--private communication.

28. Danielson, J.--private communication.

29. Terhune, R.--private communication.

30. Banks, D. C. and R. T. Saucier, Geology of *Buckboard Mesa*, Waterways Experiment Station, Rept. PNE-5001 (July 1964).

31. Toman, J., "Comparison of TNT and NM as Cratering Explosives"--to be published.

32. Cherry, J. T., "Computer Calculations of Explosion-Produced Craters," *Intern. J. Rock Mech. Min. Sci.* *4*, 1 (1967).

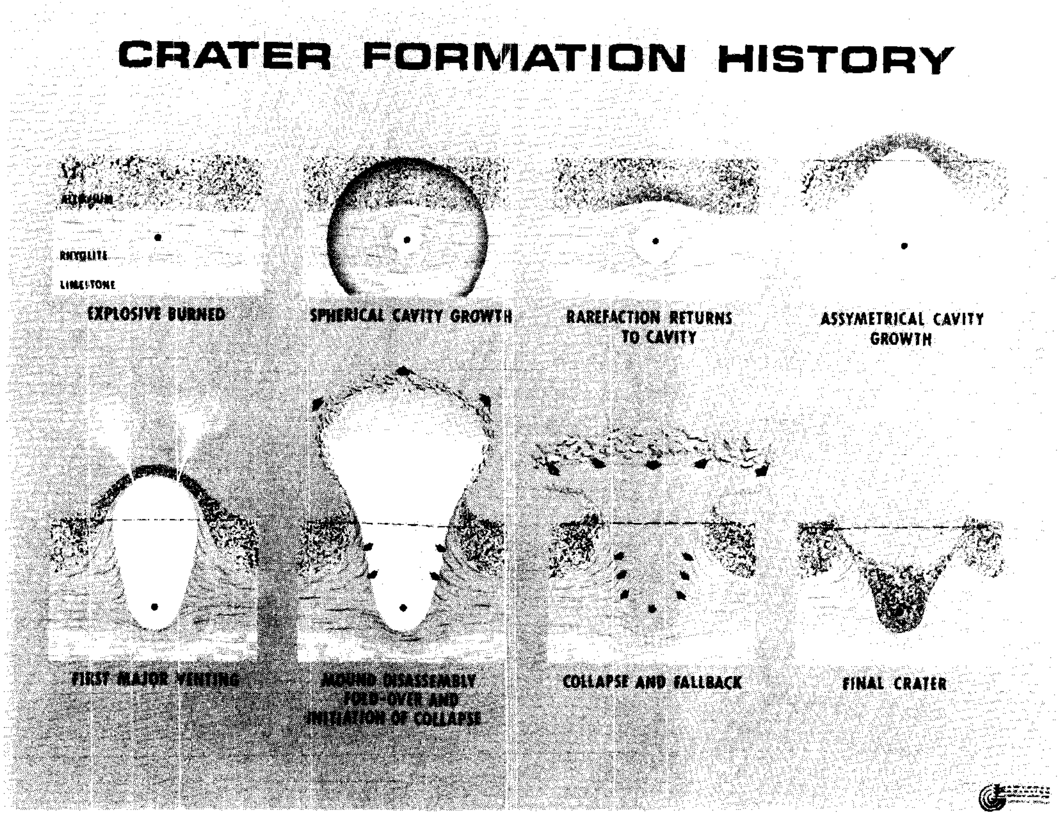

Fig. 1. Crater formation history.

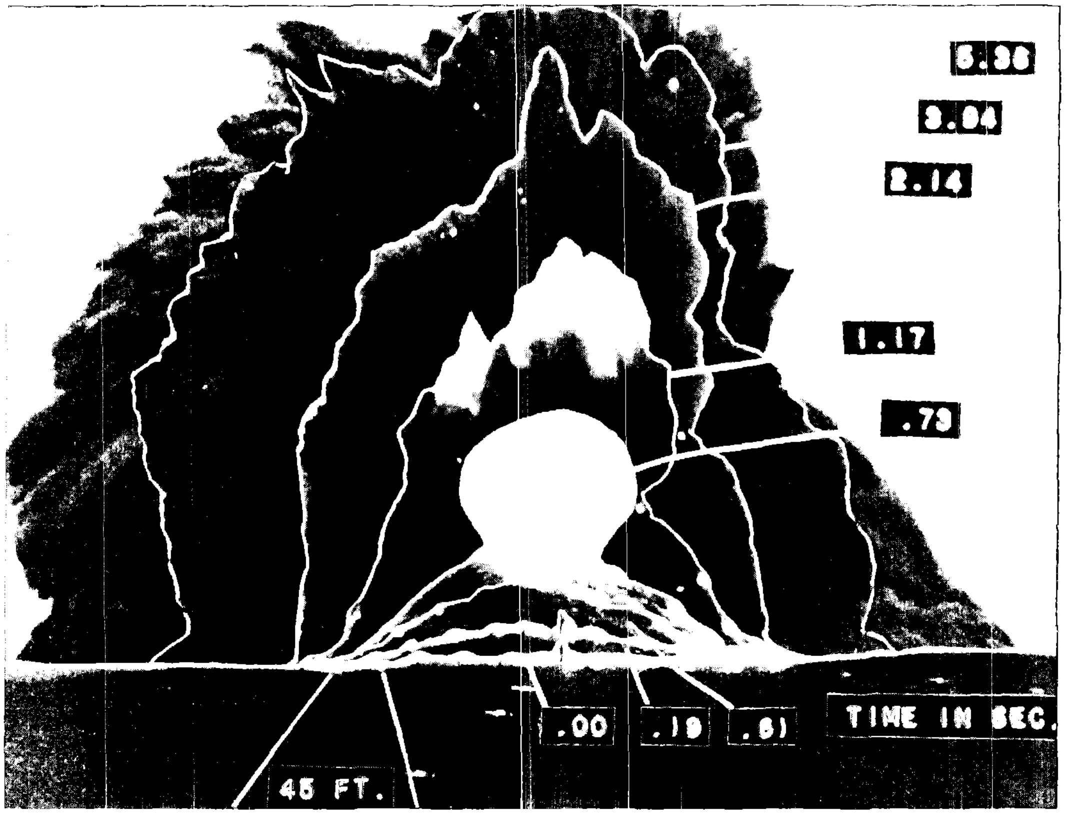

Fig. 2 Cabriolet mound development.

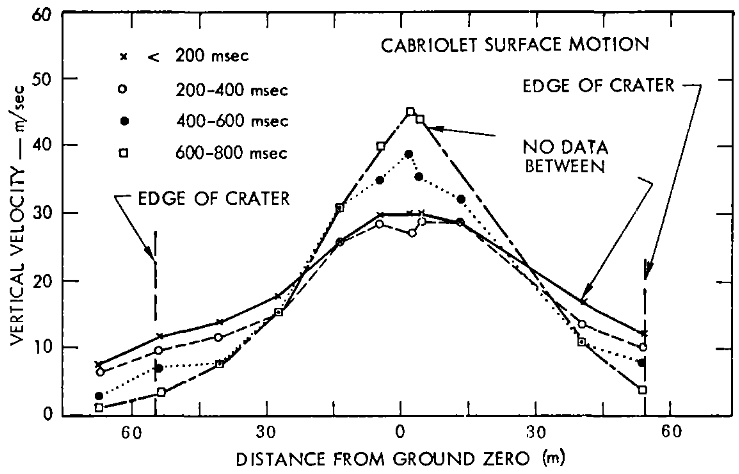

Fig. 3 Cabriolet surface motion history

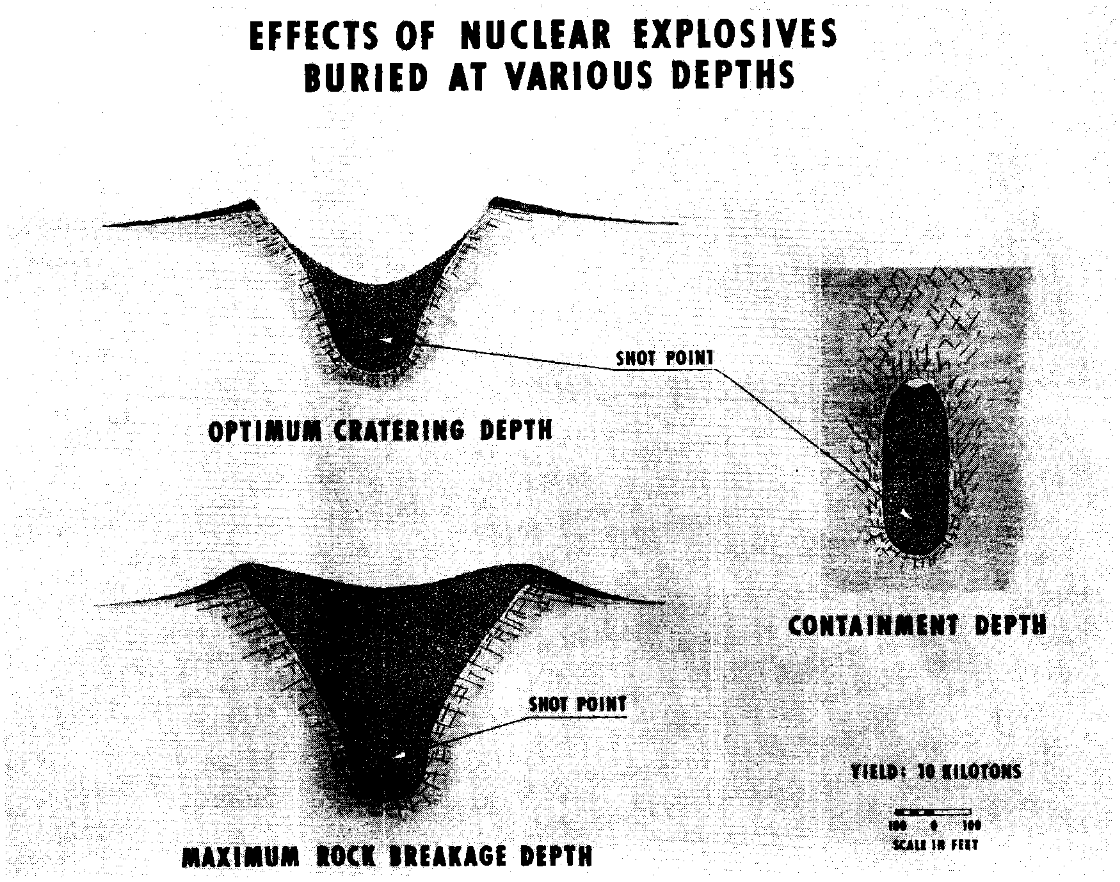

Fig. 4 Effect of nuclear explosives buried at various depths.

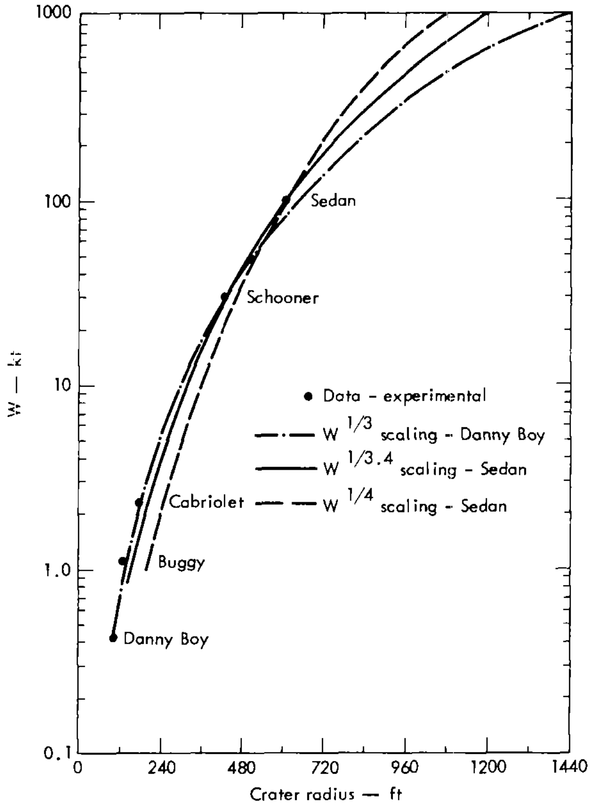

Fig. 5 Yield vs crater radius.

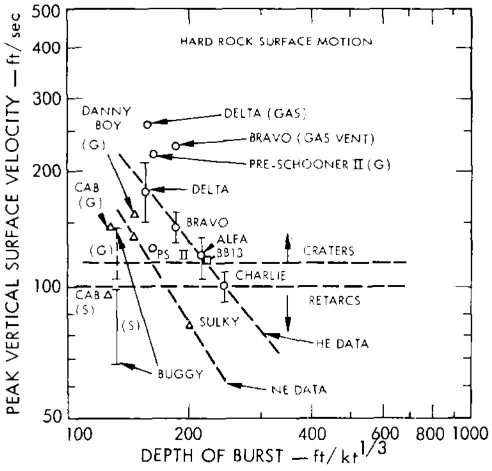

Fig. 6 Hard rock surface motion vs depth of burst.

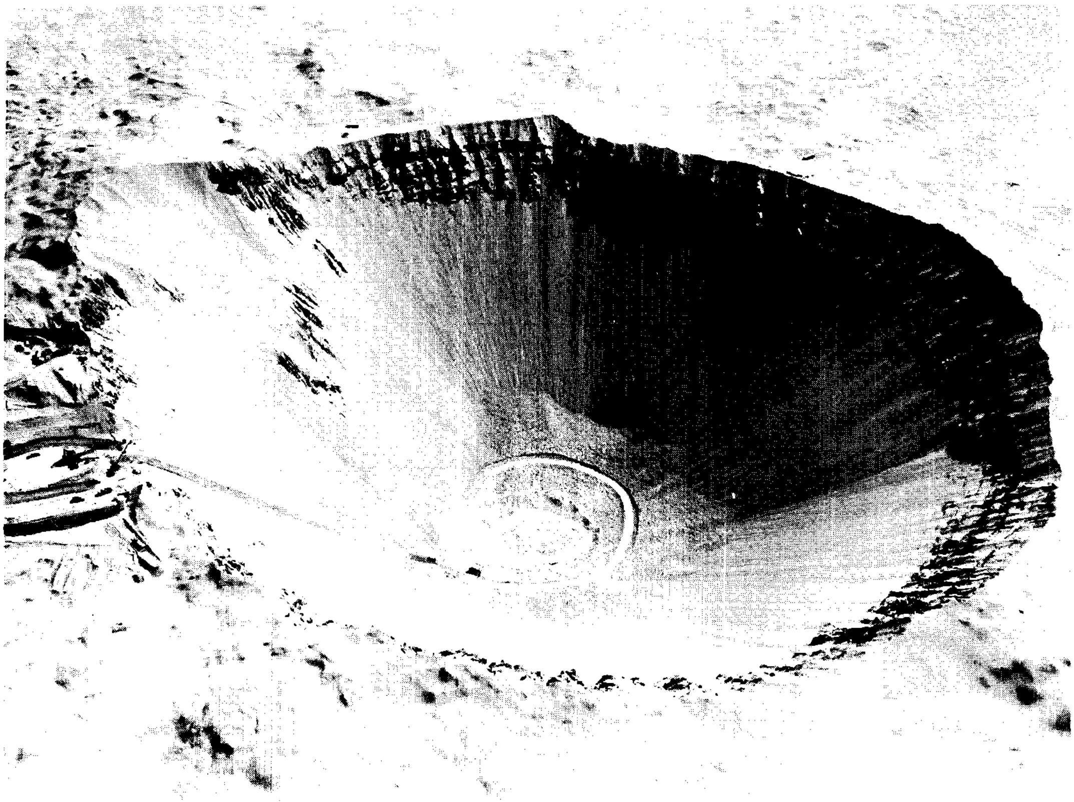

Fig. 7 Sedan crater.

Fig. 8 Danny Boy crater.

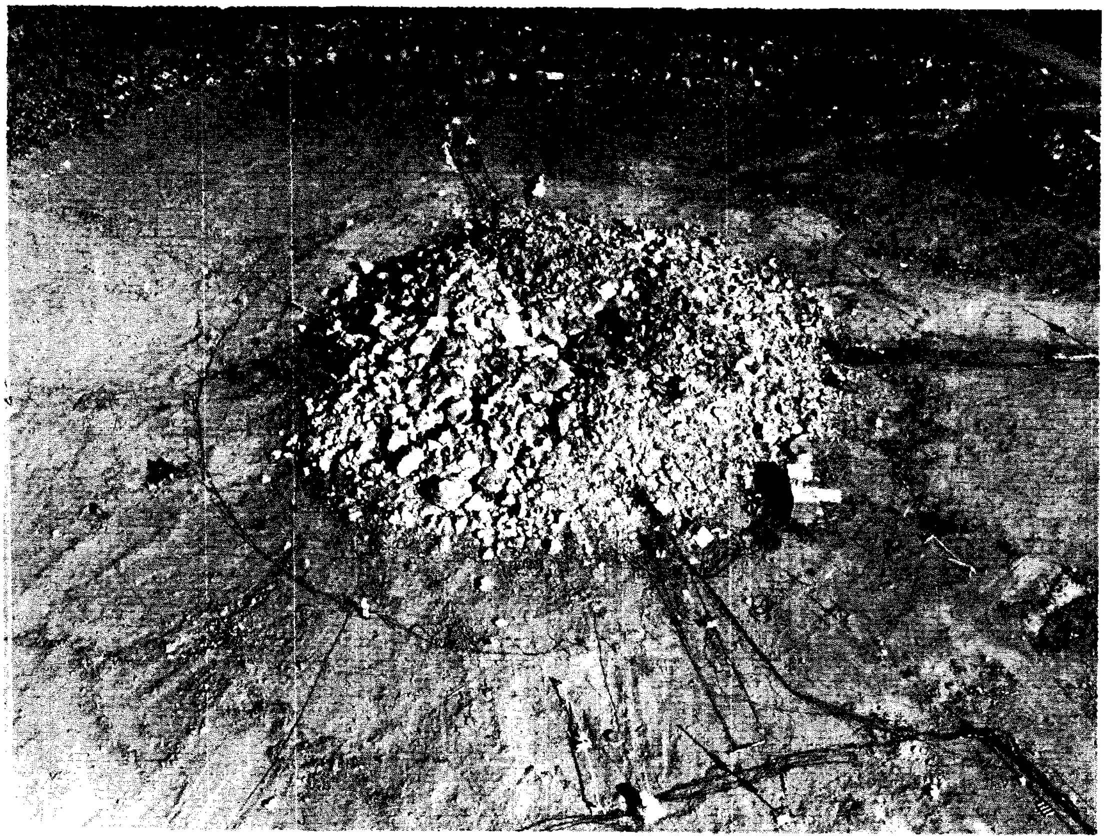

Fig. 14. Dugout crater.

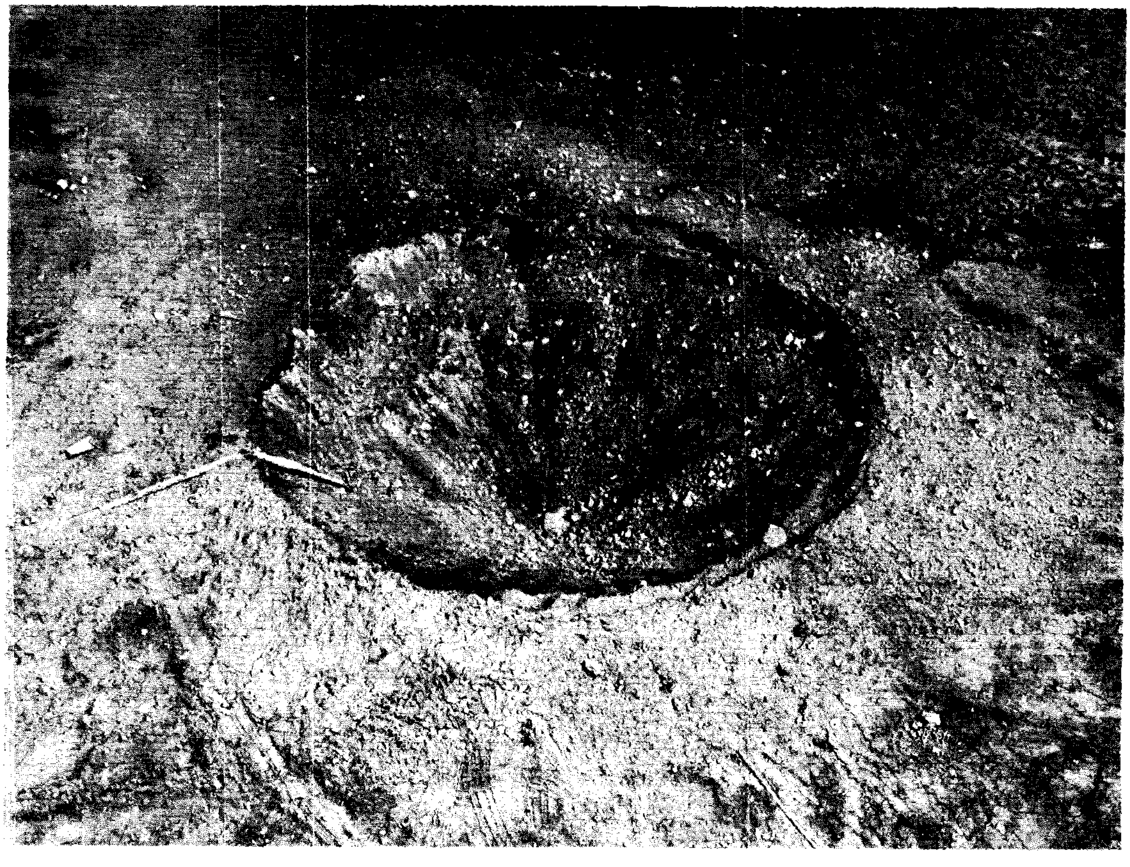

Fig. 10 Palanquin crater.

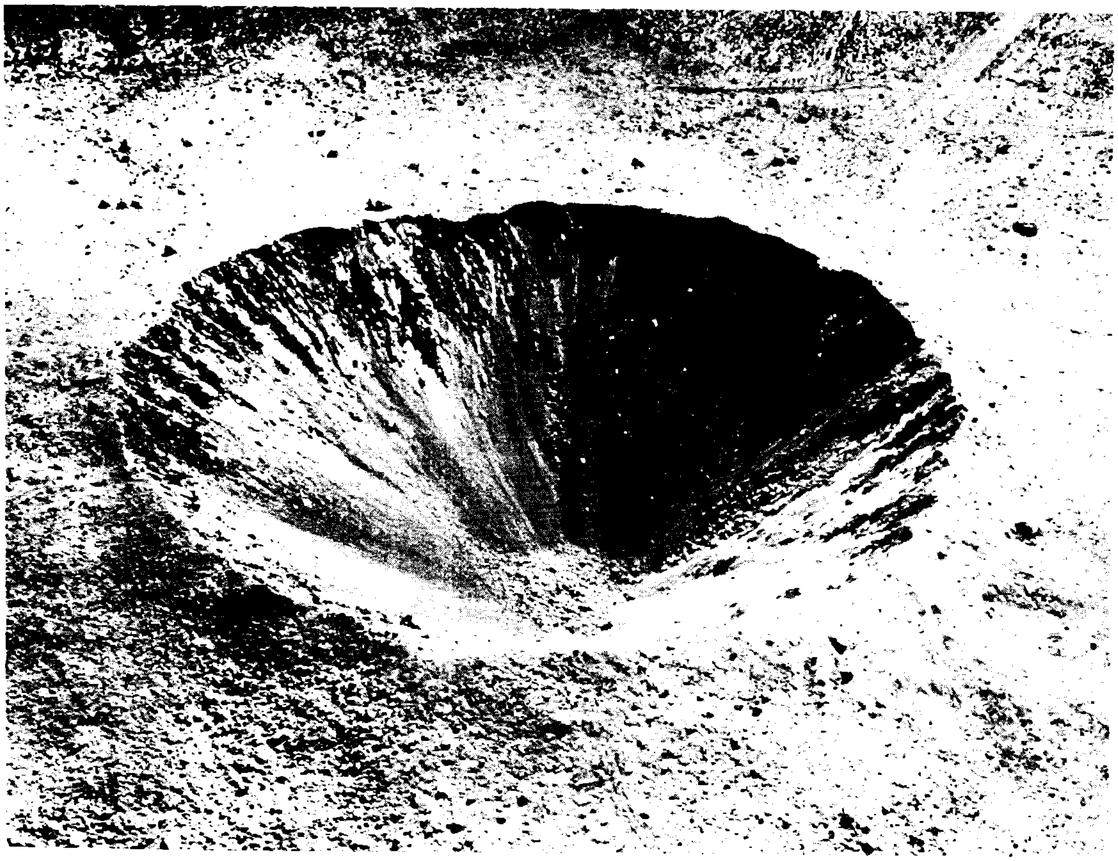

Fig. 11 Cabriolet crater.

Fig. 12 Schooner crater.

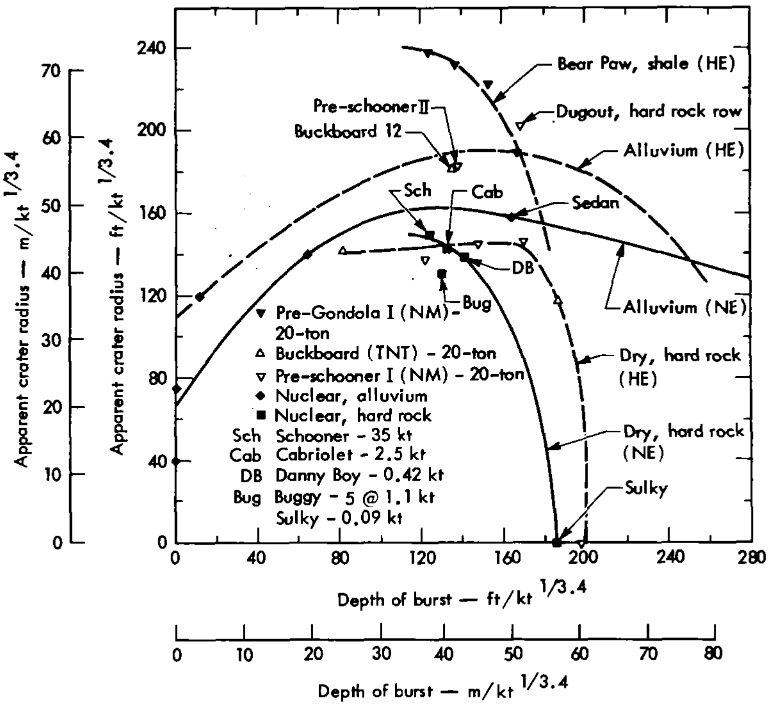

Fig. 13a. Scaled crater radius vs scaled depth of burst.

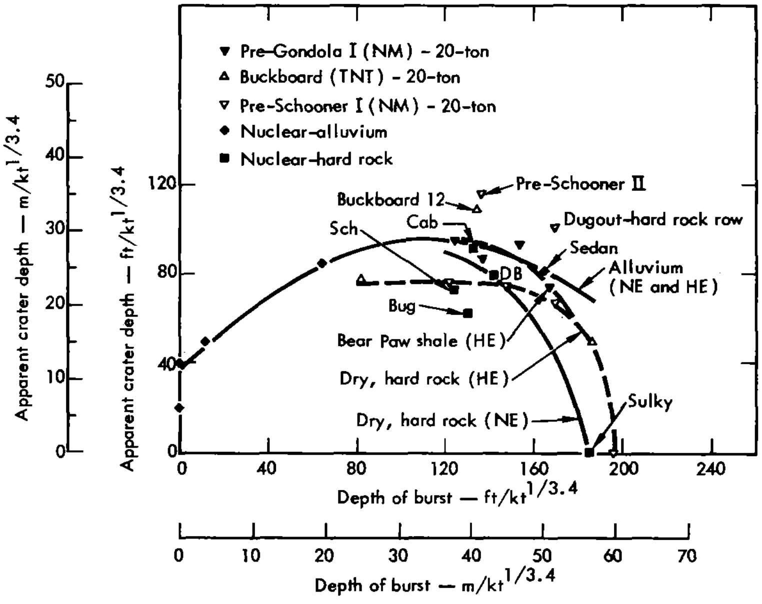

Fig. 13b. Scaled crater depth vs scaled depth of burst.

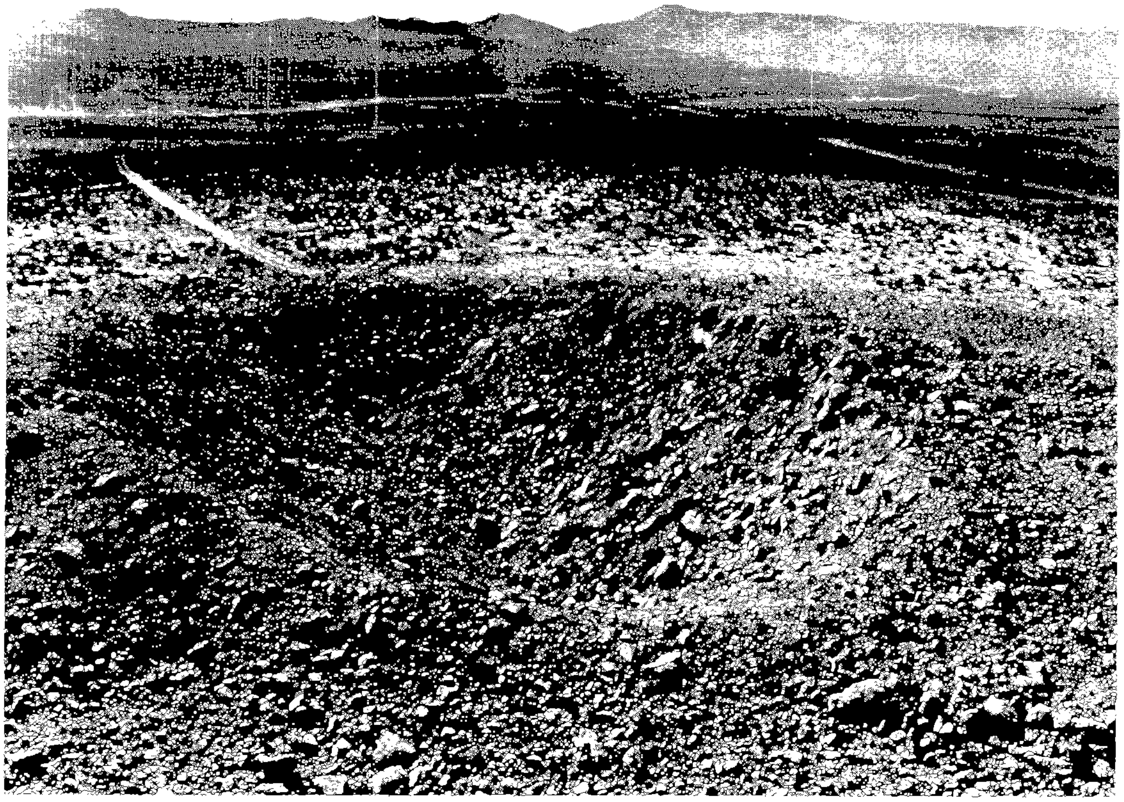

Fig. 14. Dugout crater.

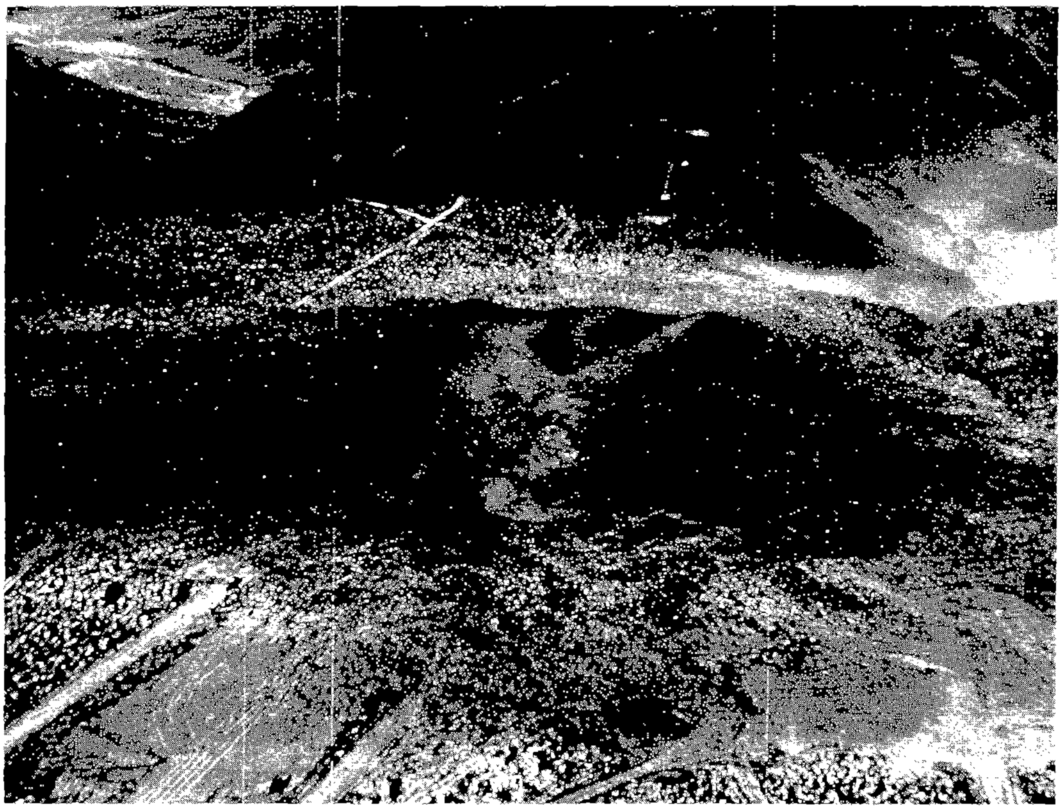

Fig. 15 Buggy crater.

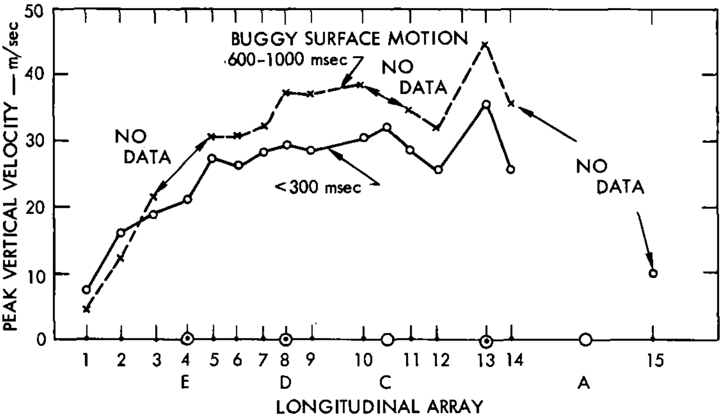

Fig. 16 Buggy surface motion history.

QUESTIONS FOR JOHN TOMAN

1. From Mr. Terrill:

   Have the data been evaluated by experienced dam designers to determine the relative cost and effectiveness of the nuclear techniques vis-a-vis other techniques? If these are published would you provide a reference?

   ANSWER:

   I really can't answer this question in detail. There is currently a study going on and that's the Aquarius study with the state of Arizona and, hopefully, there will be detailed cost estimates and comparisons made on producing dams with nuclear construction methods as opposed to conventional construction methods. That is not available right now and I'm not quite sure what the time frame is for the completion of that study in Arizona.

2. From James R. Vogt:

   What was the rock-water content at shot point for the Schooner event and what was the contribution of gas acceleration to the mechanism for this shot?

   ANSWER:

   The rock formation at the Schooner site was really a four-layered problem. From the surface down to 120 feet, the average density of the rock was 2.53 grams per cc and it was a dense, dry, competent welded tuff formation. Then from 120 to 210 feet, the average density of the rock was down to 1.5 grams per cc and the water content in this range was 8 to 10 percent and the rock was very porous and weak. From 210 feet to 337 feet, the average dry density of the rock was 1.25 grams per cc and the water content in this region was 20 to 38 percent and it was an extremely porous rock, very weak. And from 337 feet to 480 feet, and this interval included the shot point, again we were up to a very dense, competent rock with an average density of 2.53 and at the shot point the average water content was probably on the order of 4 percent, maybe 5 percent. In the code calculations that were run for the Schooner event, a good portion of the cavity was in that layer immediately above the competent dense rock and so the code calculations assumed an average of 10 percent water in the rock that was affected immediately on detonation.

Moderator: It's the prerogative of the chairman of the session to provide a further answer to Dr. Pendleton's question to Mr. Williamson concerning the question from a long-term contamination point on cratering, can savings in dollars by using nuclear explosives be defended? I believe the answer to this is yes, as long as we can keep the exposures to people down to the levels that Mr. Terrill was talking about earlier.

TECHNICAL PROBLEMS AND FUTURE CRATERING EXPERIMENTS*

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ABSTRACT

This paper reviews some of the key technical problems that remain to be solved in nuclear cratering technology. These include: (1) developing a broader understanding of the effects that material properties and water content of the earth materials around the shot have on cratering behavior, (2) extending the experimental investigation of retarc formation to include intermediate yields and various materials, and (3) improving our ability to predict the escape of radioactive material to the atmosphere to form the cloud source responsible for fallout. The formation processes of ejecta craters, retarcs, and subsidence craters are described in the light of our present understanding, and the major gaps in our understanding are indicated. Methods of calculating crater and retarc formation are discussed, with particular reference to the input information needed. Methods for calculating fallout are presented, and their shortcomings are discussed. A preliminary analysis of the safety factors associated with the presently proposed nuclear excavation concepts is presented.

INTRODUCTION

The preceding two papers have described some of the potential applications of nuclear excavation technology and the data acquired from several past nuclear excavation experiments. This paper discusses some of the key technical problems associated with nuclear excavation technology. These can be divided into two general classes:

1. Applied science problems: Those concerned with the use of nuclear excavation techniques to produce earth structures suitable for conversion into useful engineering works (canals or harbors, for instance).

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*Work done under the auspices of the U. S. Atomic Energy Commission.

2. Safety problems: Those concerned with public safety and with minimizing the adverse impact of nuclear excavation on the surrounding environment.

Excavation with nuclear explosives might make use of three different kinds of nuclear structures: ejecta craters, retarcs, and subsidence craters. These structures are illustrated in Figure 1 and briefly defined below:

A. Optimal ejecta crater. This is a crater of maximum useful volume made by detonating an explosive at the appropriate depth of burial. Experimental evidence indicates that such an optimal crater is associated with a depth of burial of about 140 ft. x $W^{1/3.4}$, where W is the number of kilotons of yield. However, layering of the geological environment or variations in physical properties of the material surrounding the shot may cause important departures from the optimal depth of burial and crater dimensions as predicted by this simple scaling which is based on yield only. Detonations in such complex geological environments must be designed with stress-wave calculation codes.

B. Retarc. A retarc--crater spelled backwards, to denote that the surface expression is the opposite of a crater, namely a mound--is a roughly conical volume of broken rock produced by an explosion at such a depth of burial that the volume of broken rubble is maximized and little of it is ejected. Retarcs are normally made in brittle rocks that bulk after failure and collapse of the mound.

C. Subsidence crater. A subsidence crater is formed by detonating a nuclear explosive in a compactable material wherein the initial cavity void space generated by the explosion at depth is, in large measure, propagated to the surface of the earth during collapse. Subsidence craters are known to form in desert alluvium, for example, at depths of burial of the order of 200 ft. x $W^{1/3}$ and deeper. In subsidence craters there is no dynamic venting and no lip formation by ejecta.

In designing nuclear projects or in performing nuclear feasibility studies a great number of practical design questions arise. Some examples are as follows: How does one emplace the nuclear explosives of a given yield to produce the desired earth structure? What fraction of the days in a given month can be considered as acceptable shot days, assuming one is given a range of dimensions of the stabilized debris clouds resulting from the shot? How do initial stabilized cloud dimensions depend on material properties and depth of burial? How large a yield can be safely detonated at the specified site from the point of view of seismic safety?

To answer such questions the Plowshare engineer or scientist requires the following:

1. A body of descriptive data concerning the nuclear effects.
2. An understanding of these effects in terms of physics and chemistry of the explosion and the site-dependent factors.
3. A predictive capability for the effects of engineering interest as well as the potentially hazardous effects which must be minimized through design or other actions.
4. Control of undesirable effects through explosive improvements or remedial measures taken on or near the structure.

All four of these aspects of Plowshare applied science must be developed in its research and development program. We shall, in the remainder of this paper, describe certain key technical problems whose solutions are necessary to develop the technology.

CRATERING CALCULATIONS

The first area we discuss is cratering physics. For several years now the Lagrangian stress wave propagation codes in one or two space dimensions have been under development in the K-Division Rock Mechanics Group. These codes, SOC and TENSOR, have been described as finite-difference solutions to stress-wave propagation through a layered geological medium including the elastic-plastic response of the materials and material failure in shear or tension. When stress levels are very high (e.g., greatly exceeding the strengths of materials), material behavior is essentially hydrodynamic. In intermediate stress regimes, the stress-wave propagation can be either elastic or plastic, including material failure. In the later stages, material behaves more like a viscous incompressible fluid. The time spent in the hydrodynamic range is yield-dependent but quite small, being of the order of a few milliseconds, whereas the duration of the latter regime is of the order of a few seconds.

TENSOR has also been described as a finite-difference equation approach to solving the conservation equations in two dimensions, including the appropriate equations of state of the materials involved and criteria for modes of material failure. Figure 2 gives the TENSOR logic loop.[1]

Figure 3 shows a typical initial condition for a TENSOR problem,[1] wherein the explosive energy is placed in a spherized source region that is isobaric and contained within an initially nonmoving geological medium appropriately zoned. An axis of symmetry runs vertically through the center of the source region; the earth's free surface is depicted as being horizontal and constitutes one boundary of the uppermost zones. To assure first-order approximations in the difference equations, the mass per zone is not permitted to change by more than 5% from one zone to another. For purposes of designating the appropriate equation-of-state information, each zone is identified as to material type.

Returning to the logic loop of TENSOR (Fig. 2), we note that this initial condition is input as the initial stress field for cratering calculations, and the law of conservation of momentum is solved in Step 1 to ascertain the acceleration for each zone element. Steps 2-5 have been adequately explained previously and involve first-order difference equations centered in time.

Step 6, the first law of thermodynamics, is solved in the finite difference form for the new specific internal energy of each zone wherein work is done by the isotropic part of the stress field as well as by the deviatoric stress field. From this conservation law, any changes of phase can be determined. The mean stress and the stress deviator are calculated for each zone in view of its displacement history. Failure criteria are then tested to see if the material has failed either in shear or tension; if so, the stress field is adjusted from laboratory-determined pressure-volume relationships, assuming that zone volume is conserved in the failure process. After this adjustment of the stress field, new initial conditions are thereby generated for Step 7, and the evolution of the system has been advanced an increment of time, Δt.

The physical properties of rock materials necessary for this code include the following:

1. Hydrostatic pressure versus specific volume for both consolidated and failed materials under loading and unloading cycles. This information is determined in the laboratory for representative samples, in the pressure range 0 to 40 kilobars.

2. Hugoniot measurements to extend the pressure-versus-specific-volume curves into the pressure range of 40 to approximately 800 kilobars. (Above 800 kilobars, theoretical models of the equation of state are employed.)

3. The maximum stress deviator that can be supported as

a function of mean stress for both consolidated and failed material.

4. Other properties of the materials such as tensile strength, elastic limit, Poisson's ratio, compressional velocity consistent with the low-pressure P-V information, and the gas equation of state for natural rock materials having various water contents.

To illustrate a cratering physics calculation we show some of the calculations for the Danny Boy event, a 0.42-kt nuclear explosion at a depth of 33 meters (109 ft) in basalt. This case study represents an *ex post facto* cratering calculation. As indicated above, the energy yield of the explosive was placed in a spherized source region 1.8 m in radius centered at the 33 meter level. Since the medium was dry, the relatively simple equation of state of vaporized basalt was used in this gas region (see Fig. 4 for initial condition).

Figure 5 shows the cavity configuration and free-surface earth configuration at 97 msec. At this late time, of course, the compression wave and rarefaction wave had completed their respective travels to and from the earth's surface, and a very weak recompaction had started back towards the earth's surface in the region above the cavity. However, it was observed that at this time of 97 msec the pressures in the cavity were quite low due to the dryness of the Danny Boy shot environment. The pressures in the surrounding medium at this time were also low. In view of these low pressures, a concept was developed that the material in the mound had by this time received all the momentum to be imparted to it by the explosion. Accordingly, from this time onward all zones in the problem were subjected to a simple ballistic missile calculation using the initial condition of the velocity for the mass center of each zone at 97 msec. With this concept, the mass deposition on the original earth's surface can be calculated as can the designation of those zones which have insufficient velocities to be ejected from the crater.

Figure 6 shows the predicted mass deposition and the calculated true crater configuration. Superimposed on this figure also are the apparent crater configuration, the observed true crater configuration, and the postshot earth's surface. The agreement between the observed and calculated true crater boundaries and mass deposition depth is excellent. This concept of calculating the mass deposition provided a new and valuable tool for estimating not only the apparent crater radius but the ejecta from a cratering event as well. This analysis indicated that the principal cratering mechanism for Danny Boy was spall, induced by the stress wave.

From other postshot cratering calculations that were performed, a primitive method of predicting apparent crater depth with the TENSOR calculation emerged. In this method, the depth of the crater is estimated by allowing the mass deposition above the zone of ejection to fall into the calculated true crater volume, including the effects of bulking and any estimated slumping of unsupported subsurface material. Table I summarizes the results of a few calculations (R. W. Terhune, of LRL, private communication, 1968).

CRATER FORMATION HISTORY

From these calculations as well as others cited by the author,[2] we can formulate representative crater formation history (Fig. 7). The geometries depicted in this history have been taken in large measure from the TENSOR calculation of Danny Boy. Thus, the spatial scale for this diagram is that the shot depth is approximately 42.6 m x $W^{1/3}$. Experimental data from many events and from small-scale cratering model studies by the Corps of Engineers have contributed to this diagrammatic representation. The crater formation history, as we understand it today, contains seven phases:

1. Vaporization of the explosive and a surrounding shell of earth materials.

2. A period of spherical cavity growth.

3. Return of the rarefaction wave to the upper cavity surface.

4. Asymmetrical growth of the cavity, with the upper part growing rapidly following rarefaction return as contrasted to very slow growth of the lower hemisphere at this time.

5. Mound growth until the time of venting.

6. Mound breakup with foldover and the initiation of collapse in the subsurface layers.

7. Collapse, fallback, and mass deposition beyond the point of foldover.

In this context, a very simple concept for optimal cratering configuration emerges: namely that, despite the layering or different material properties of the shot environment, an optimal crater is obtained from a given energy source by optimizing the calculated mass deposition beyond the foldover point so that a maximum volume of effectively ejected material is obtained.

It is important in regard to the crater formation history to comment that the two cratering mechanisms, spall and gas acceleration, the crater dimensions, and the optimal depth of burial may all be functions of material properties. The physicists making these stress-wave propagation studies have, as a result of many calculations, developed a considerable fund of experience. Their experience indicates that the compactability of a material influences how good a stress wave propagator it is; the shear strength as a function of mean stress varies from material to material with water content and the degree of saturation; the sound speed in the material dictates, in part, how dominant the spall mechanism is; the unloading characteristics of the material are important in terms of energy available for cratering; the water content of the material influences the cavity pressure at late times, and hence the gas acceleration. Thus, depending on the host material, the history of the formation of a crater may change, the dominant cratering mechanism may change, and the feedback between them may change. The data contained in Table I indicate that craters can be successfully predicted in materials of very different properties.

With this background then, let us turn to some of the key problems that still confront us in regard to cratering physics. First of all, we need a broader understanding of crater formation history. For example, the crater formation history for a standard 1-kiloton source, say, at optimal depth of burial should be developed for very different rock types ranging from weak saturated shales to dry dense rock. Ideally these crater histories would be developed in parallel under one another with remarks concerning the timing and relative importance of the cratering mechanisms in the materials as a function of time. In this way engineers and scientists could see the difference in the cratering characteristics of various materials responding to a standard source.

The calculational program required for such a development would not be a quick program; however, I believe its objectives are within our capabilities to accomplish, given the necessary resources.

The second key technical problem is to extend our nuclear-cratering predictive capability to include shots of high yield in relevant materials. This is essential to acquire data for the design of harbors and excavations like the sea level canal in Central America. This step would be accomplished by a coordinated calculational and experimental program. The Yawl, Phaeton, Gondola series planned by the Atomic Energy Commission for the future would address itself to high yield detonations in materials that vary in water content, degree of saturation, and density. (A more complete "shopping list" of technical questions and problems is presented in UCRL-71216.[2])

RETARC CALCULATION

The first and only stress-wave propagation code calculation of a nuclear retarc is for the Sulky event, a 0.1-kt nuclear explosion at a depth of 27.4 m (90 ft.) in dry basalt. We now briefly review the essential points of this calculation.

Because of its deep burial, the Sulky detonation produced a mound of rubble but not a crater. The strategic question here is to ascertain if this result could have been predicted. The TENSOR postshot calculation (Fig. 8) shows the zones calculated to remain in the subsurface environment, the ejected surface mass deposition, and the cavity configuration, at 76 msec after detonation. The figure definitely shows that the mass deposition within the true crater is comparable in depth to that ejected beyond the edge of the true crater boundary. If this mass of material is placed back in the true crater, making allowance for bulking, we find that indeed no crater is formed. This indicates that the calculation of mass deposition from a buried source is an important tool, not only for predicting the apparent crater radius, but also for predicting whether a useful structure will be formed.

The mass deposition shown in Figure 8 for Sulky is markedly different from that calculated for the Danny Boy event (Fig. 6). These two calculated mass depositions were taken as models for the mass deposition that would lead to a useful crater and the mass deposition that would lead to a retarc. The mean mound velocities as developed in Danny Boy and Scooter (½ kt HE shot) were on the order of 40 to 50 m/sec, and those developed in Sulky were 23 to 26 m/sec.

RETARC FORMATION HISTORY

The retarc formation history shown in Figure 9 has been constructed on the basis of the Sulky calculation. Geometrical relationships in this diagram are based on a depth of burial of about 55 m x $W^{1/3}$. The stages of formation are quite similar to those of the crater (Fig. 7), with the exception that in the retarc the mound undergoes no development of a foldover point and the mass ejected beyond the true crater boundary is not large. Under these conditions the fallback material and the subsurface collapsing material, with their volume increased by bulking, can more than fill the void created during the cavity.

There is much room for improvement in our understanding of retarc formation history. Two main problem areas are as follows:

1. The sensitivity of the mechanics of retarc formation to material properties such as those listed for cratering is not well explored. We have the roughly sketched physical picture that retarcs will be made in deeply buried shots in a brittle dense rock that bulks upon collapse; however, we don't know how much compaction a rock type might have and still be able to support retarc formation for some combination of yield and emplacement depth.

2. We have no intermediate-yield retarc experimental experience; the only retarc made thus far was by a 0.1-kt nuclear explosion at 90 feet. A retarc structure of commercial interest would probably require a yield of 10 to 200 kilotons. At present no retarc experiment of this type is planned.

SUBSIDENCE CRATERS

Subsidence craters in this paper are mentioned more for the sake of completeness than for their present interest to the Plowshare program. It is indeed true that parts of the Nevada landscape are pocked with subsidence craters whose formation the test engineers have been able to predict with confidence from simple engineering relationships. From one point of view subsidence craters are very interesting: they are reasonably large depressions in the ground produced with minimum impact on the surrounding environment. Radioactivity release is minimal because there is no dynamic venting; no ejecta lips are formed, and the sides are gently sloped (roughly 1 in 4). Imaginative engineers may yet find a reasonable use for this type of structure at suitable sites.

PREDICTION OF FALLOUT FROM CRATERING DETONATIONS

The objective of our research on fallout from nuclear cratering detonations has been to develop a capability for predicting airborne concentration, surface air concentration, surface deposition of specific radionuclides, and the gross gamma radiation field. The predictions include the effects of (a) atmospheric transport, (b) atmospheric eddy diffusion, (c) suitable initial cloud geometries for different detonation environments, (d) precipitation scavenging, if any, and (e) released fractions of significant radionuclides, if known or estimated. Two numerical simulation models for fallout have been developed over the past several years. The first is a close-in fallout model,[3] and the second is a long-range, two-dimensional dispersion model developed by Crawford.[4-7] Table II gives a brief description of these models.

Tests of the predictive capability of the KOFC model have been conducted using actual cloud geometries, cloud source, and shot time winds for the Danny Boy event. By cloud source we mean that fraction of the radioactivity that was deposited in the close-in fallout pattern between the maximum radius reached by significant ejecta and the extrapolated infinite range. The model deals with activity on particles 10 microns in diameter and larger. The postshot calculation of Danny Boy is shown in Figure 10. The good agreement between the curves of observed and predicted dose rate versus distance indicate that--given the correct input for cloud geometry, cloud height, source, and wind conditions--the exposure rate is quite predictable. We have, in general, run enough such problems on the computer to develop an experience for sensitivity of the solutions to input. Two of the more sensitive parameters are the assumed source and the cloud height, which under certain meteorological conditions can have profound effects on trajectory.

Some of the key needs in developing fallout prediction capability include (a) improvement of prediction of base surge dimensions, (b) improvement in prediction of energy vented to the atmosphere and available to drive the generation of the main cloud, (c) study of the mechanisms of precipitation hot spot formation, and (d) an examination of existing data on the hot spot formation with a view to learning how to avoid it for periods up to two days.

One way to begin on some of these problems is to build a numerical simulation model of the venting of the cavity gas through an "average mound fissure" associated with a cratering detonation. We have taken the initial steps in this direction by adapting the code called PUFL to this problem. PUFL is a semi-Lagrangian 1-D code for calculating the flow of hot gases in expanding pipes of arbitrary dimension(analogous to fissures opening in the mound); the code includes the effects of friction and mass entrainment or ablation of material from the wall on the thermodynamics and hydrodynamics of the pipe flow.[8] During the evolution of the pipe flow, the input to the entry section of the pipe is a continuous flow of gas from a source of a prescribed pressure-time history. In applying this code to the cratering shot, Danny Boy, we assume that after the rarefaction wave returns to the cavity the cavity gas is free to flow into the fissures developing in the mound. At this late time, the pressures in the solid material of the mound are low and the mound is divergent. We assume that it is this divergence that opens up fissures in the mound during the remainder of its growth so that gas flows upward. The observed vent time for Danny Boy was about 600 msec. If the PUFL code is run without any ablation or mass entrainment, we find that starting with initial conditions at 135 msec it is impossible to match the vent time--that is, the shock and the cavity gas travel through the fissures and arrive at the earth's surface much too fast (in 12 msec). The resulting conclusion is that material is entrained in the cooling, expanding cavity gas. By adjusting rates of entrainment, we are able to estimate the mass of material that must be entrained in the cavity gas during its movement through the mound. The results of these numerical experiments indicate that material having approximately 10 times the mass of the cavity gas must be entrained in order to reproduce the observed vent time. This mass entrainment constitutes a considerable dilution in momentum of the venting gas. It is entirely conceivable that for a quite deeply buried shot this constitutes a quenching mechanism that contributes to decreasing the escape of radioactivity. It is known that only a small amount of radioactivity gets out of a nuclear retarc.

It is relevant to ask: What experimental data exist to confirm the results of this Danny Boy venting calculation? In this regard, we wish to cite the work of Dr. Robert Heft (Bio-Medical Division, LRL). In examining samples of fallout particles and airborne particles from cratering shots, he has discovered that there are two components of fallout. The first component is composed of larger spherical particles that have condensed from a vaporized state; the second component is composed of smaller crystalline particles that have not been vaporized. The first component has radioactivity distributed throughout the material of the particles, while the second component has radioactivity only on the surface of the particles. The two components in regard to mass exist in a ratio of about 1 part from vaporized-condensed material to 10 parts entrained material (Heft, private communication, 1969).* Although we have done only one calculation and compared it with the independent information just cited, this first model of venting appears promising in that it represents an initial-value physics approach to the problem of estimating vent time, energy put into the atmosphere, and hence on into the main cloud height problem and the airblast source problem from venting. Until this model is further perfected we will continue to make the calculations as in the past. The degree of success of these present methods of calculation is being reported by my colleagues, Dr. Tewes and Dr. Crawford, in their papers to this symposium.

*It is also interesting to note that the mass weighting factor reported by Heft and independently evaluated with these PUFL venting calculations corresponds very well with that found in computer simulation of fallout from Danny Boy and Sedan.[3]

It is perhaps appropriate in view of the theme of this symposium to conclude this paper with some projections of the different nuclear effects associated with the nuclear excavation concepts presented previously by Mr. Williamson. This summary is included in Table III to provide information that may be useful in preliminary evaluation of sites for applying nuclear excavation concepts. The models used in making these predictions of effects have been summarized and discussed previously (Ref. 2).

It is, of course, impossible in a single paper to discuss in depth all of the key problems associated with the development of nuclear cratering technology. We have, in this paper, illustrated some of the more central issues; a more complete listing of the key problems has been given by the author in a previous paper.[2] The main purpose of this paper is to expose some of our main problems to your view in the hope that some of you in this audience, or perhaps some later readers of the paper, may be able to help supply us with the answers we need.

ACKNOWLEDGMENT

The author would like to express his appreciation to Mrs. B. K. Crowley for performing the PUFL calculations of Danny Boy on the CDC 6600.

REFERENCES

1. Cherry, J. T., "Computer Calculation of Explosion-Produced Craters," *Intern. J. Rock Mech. Min. Sci., 4* (1967), pp. 1-22.

2. Knox, J. B., "Nuclear Excavation: Theory and Applications," *Lawrence Radiation Laboratory, Livermore,* UCRL-71216 (1969), p. 120.

3. Knox, J. B., "Prediction of Fallout from Subsurface Nuclear Weapons Tests (1965), pp. 331-353.

4. Crawford, T. V., "Predicting and Sampling Nuclear Clouds from the Viewpoint of Diffusion Theory," Lawrence Radiation Laboratory, Livermore, UCRL-14983 (1966).

5. Crawford, T. V., "A Computer Program for Calculating the Atmospheric Dispersion of Large Clouds," Lawrence Radiation Laboratory, Livermore, UCRL-50179 (1966).

6. Crawford, T. V., "Atmospheric Diffusion of Large Clouds," Lawrence Radiation Laboratory, Livermore, UCRL-70540 (1967).

7. Crawford, T. V., "The Long Range Diffusion of the Effluent Cloud from the Phoebus 1B EP-IV Reactor Test of February 23, 1967," Lawrence Radiation Laboratory, UCRL-50418 (1968).

8. Crowley, B. K., "PUFL, An 'Almost-Lagrangian' Gasdynamic Calculation for Pipe Flows with Mass Entrainment," *J. of Comp. Physics,* Vol. *2,* No. 1 (Aug. 1967), pp. 61-86.

Table I. Summary of predicted and measured crater dimensions.

Event	Yield	Depth of burst(Dob)		Radius (R_a), m		Depth (D_a), m	
		ft	m	Predicted	Measured	Predicted	Measured
Danny Boy (nuclear)	0.42 kt	109	33	33	33	21	19
Pre-Schooner II[a] (high explosive)	85 t	71	21.6	27	29	19	19
Pre-Gondola Bravo (high explosive)	85 t	46	14	17	24	14	9

[a] Calculation performed with the SOC-PUSH model.

Table II. Subproblems considered in fallout models.

Subproblem	Close-in fallout, particles with radius>10μ (KFOC model)	Long-range fallout, particles with radius>10μ (2BPUFF model)
Source	Stabilized cloud volume and inventory of radionuclides released	Same
Transport	(a)Horizontal wind field at shot time, or (b)predicted wind field in space and time, if available	Trajectory of cloud center and mean speed of cloud center
Diffusion	Horizontal eddy diffusion	Horizontal and vertical eddy diffusion
Deposition	Dry deposition by gravitational sedimentation	Dry deposition by vertical diffusion and impaction; wet deposition by washout process
Exposure	External gamma exposure; exposure contribution from certain significant nuclides	Airborne concentration, or surface concentration, pCi/m^2

Table III. Estimated nuclear and seismic effects associated with various nuclear excavation concepts. In all cases the shots would be fired during a period of "no return" to minimize the airblast problem.

Purpose of nuclear structure	Detonation yield[a]	Type of event[b]	Distance to 0.17 rad/year	Iodine distribution radius	Distance to 1 cm/sec ground motion
Aggregate production	∿50 kt	R	3 mi	12 mi	∿35 km (alluvium)
Retarc for leaching (5 shots)	50-100 kt	R	∿10 mi	∿25 mi	∿50 km (alluvium)
Harbors	1 Mt	C	85 mi	40-50 mi	130 km
Craters for water resources development	∿1 Mt	C	H	H	∿130 km
Crater lip dams	∿1 Mt	C	H	H	H
Overburden removal	∿1 Mt	C	H	H	H
Bulk dams	∿50 kt	R + C	∿10 mi	∿25 mi	∿35 km

[a] These yields apply to applications likely to be made in the near future.

[b] Nomenclature: C = cratering, H = approximately as evaluated in the Harbor Concept, R = retarc.

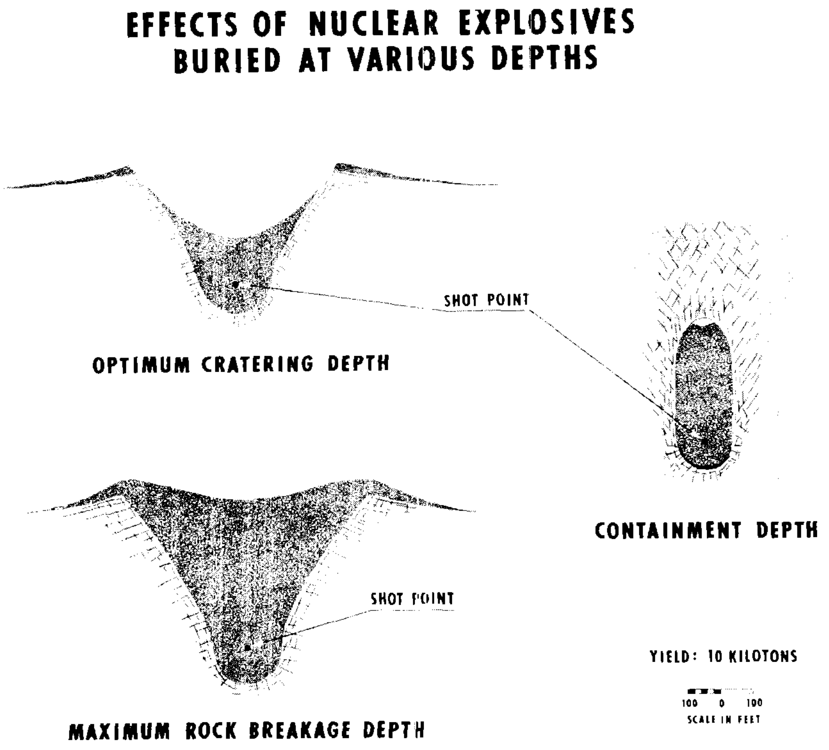

Fig. 1. Types of nuclear craters.

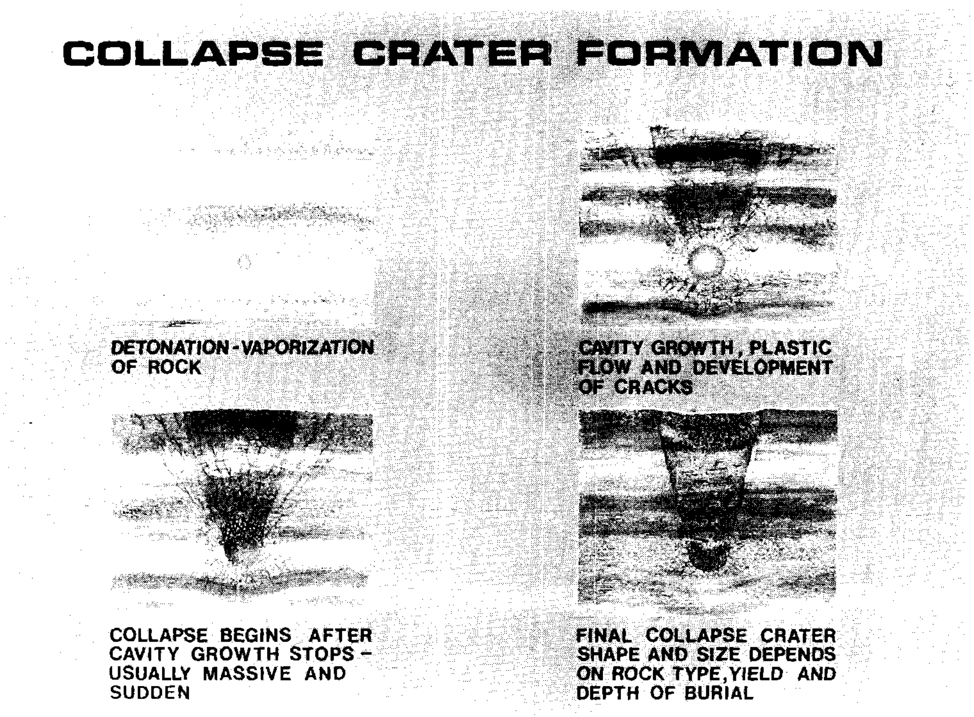

Figure 1. Types of nuclear craters (continued).

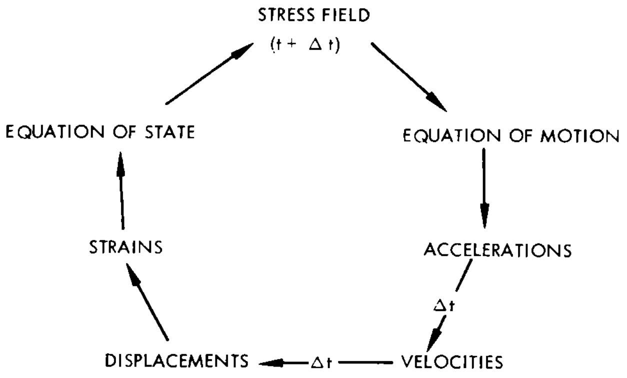

Fig. 2. Feedback loop for stress-wave propagation.

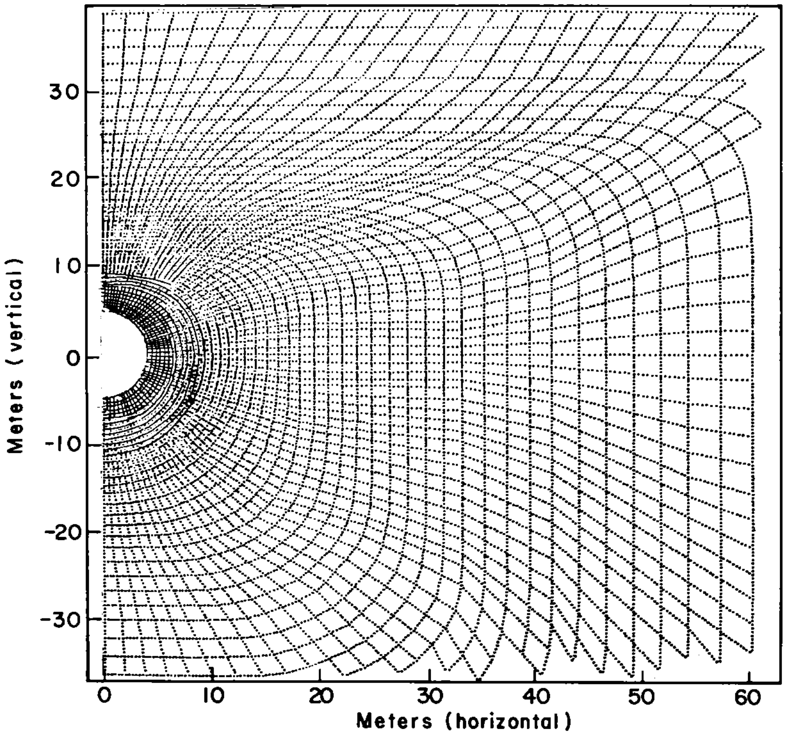

Fig. 3. TENSOR zoning for the Scooter event at the start of the calculation.

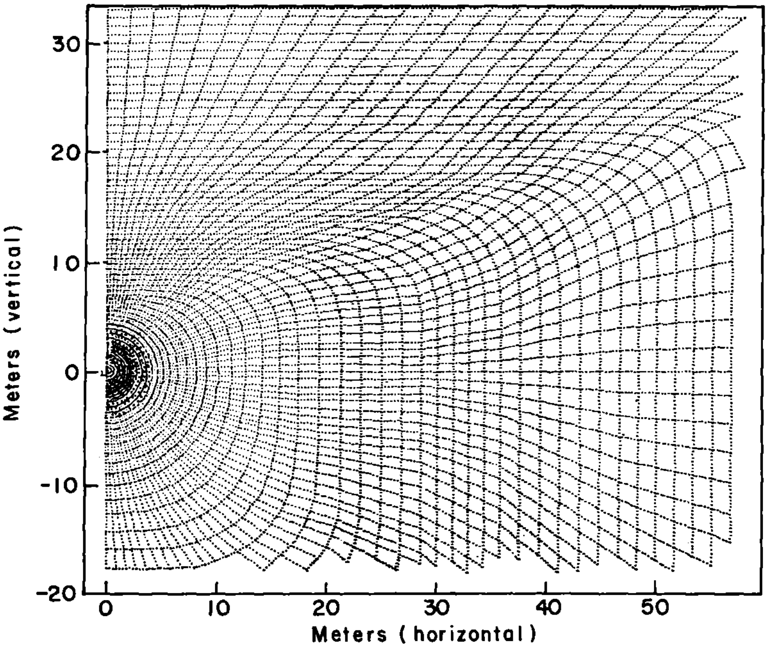

Fig. 4. Cavity and mound configuration for the Danny Boy event at zero time in the calculation.

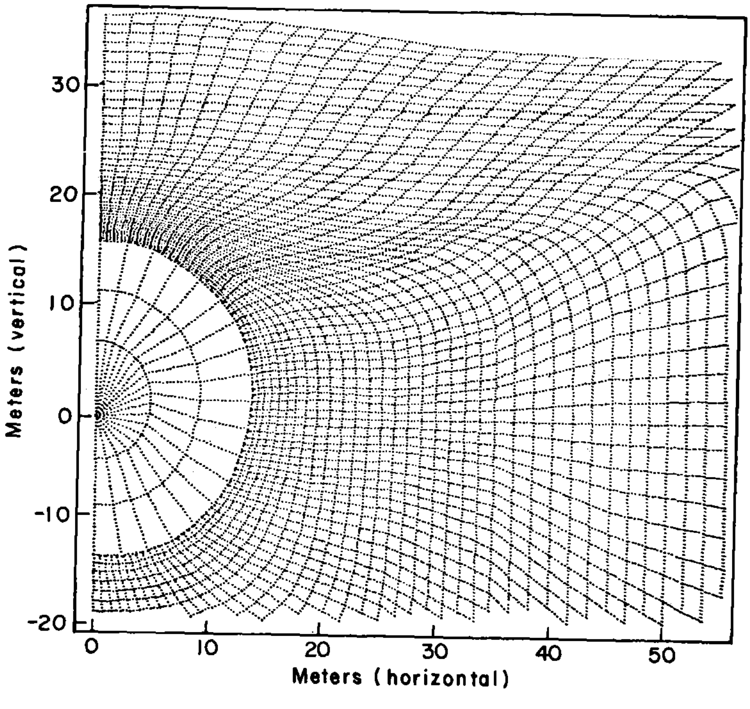

Fig. 5. Cavity and mound configuration for Danny Boy at 97 msec.

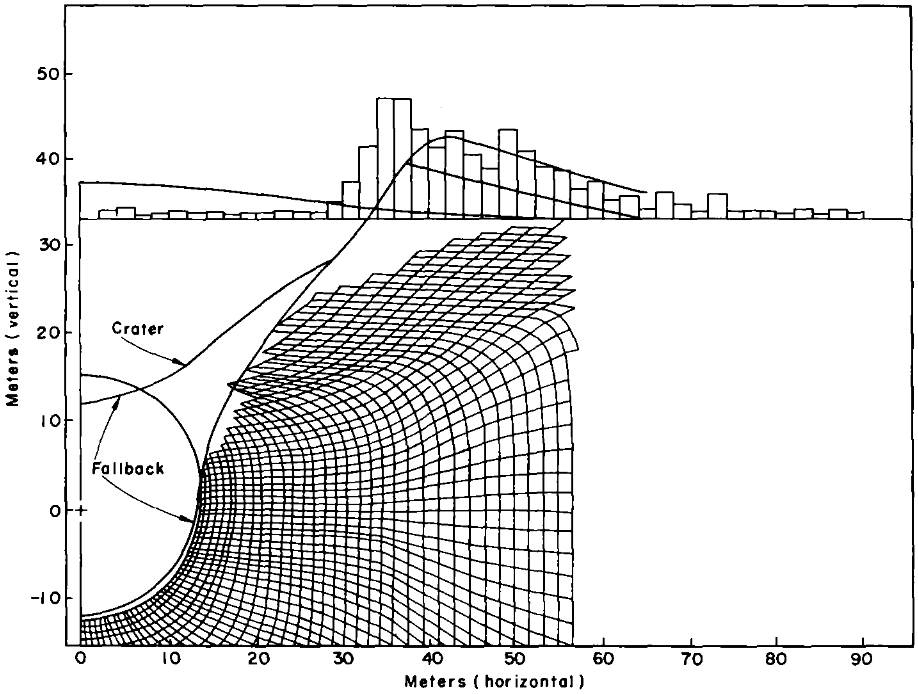

Fig. 6. Free-fall throwout calculation for the Danny Boy event at 100 msec.

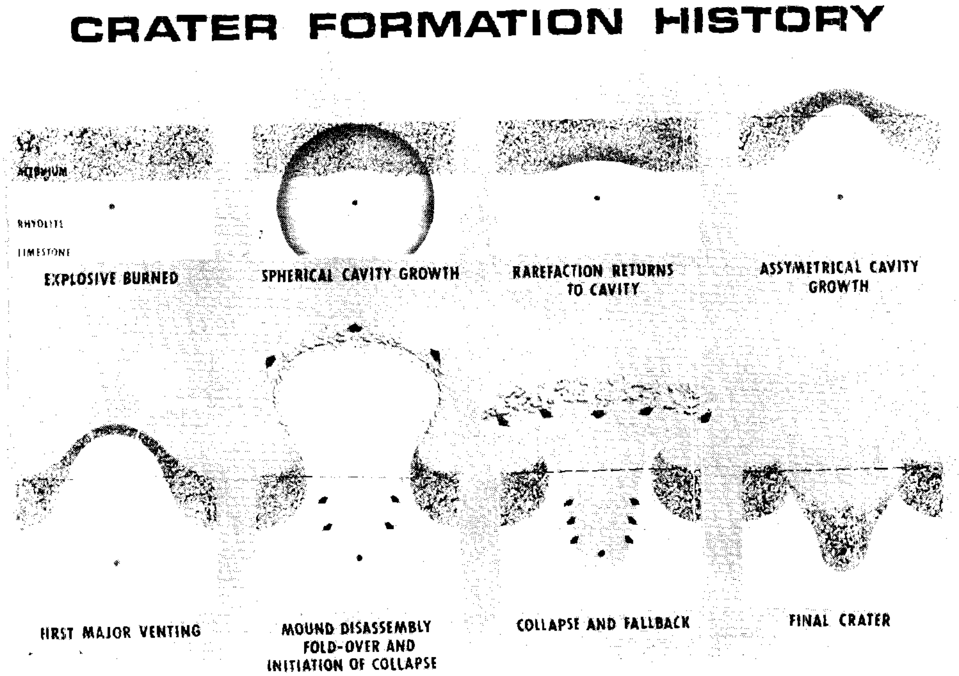

Fig. 7. Crater formation history.

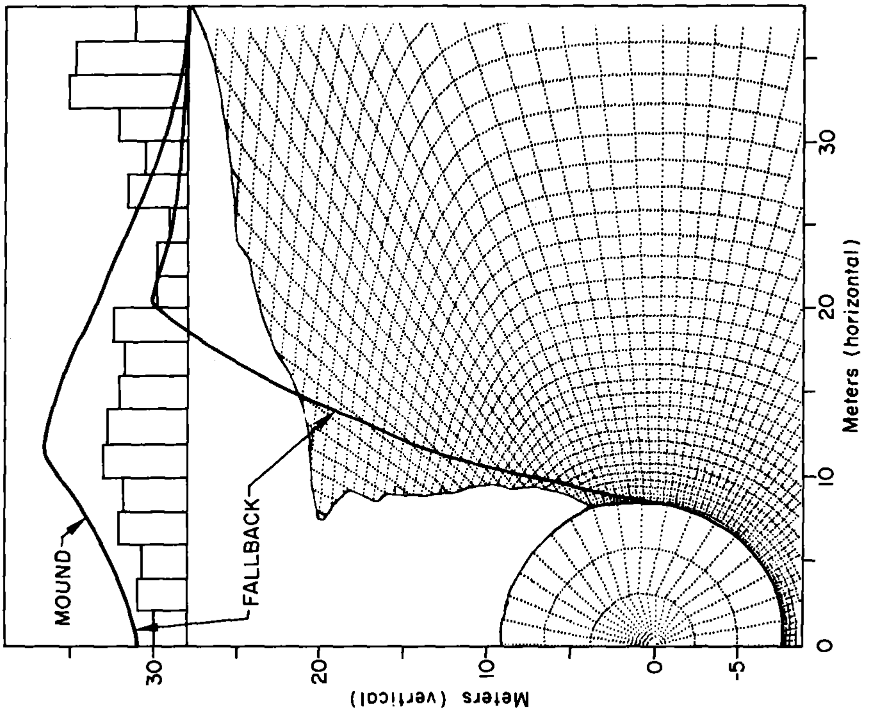

Fig. 8. Free-fall throwout calculation for the Sulky event at 76 msec.

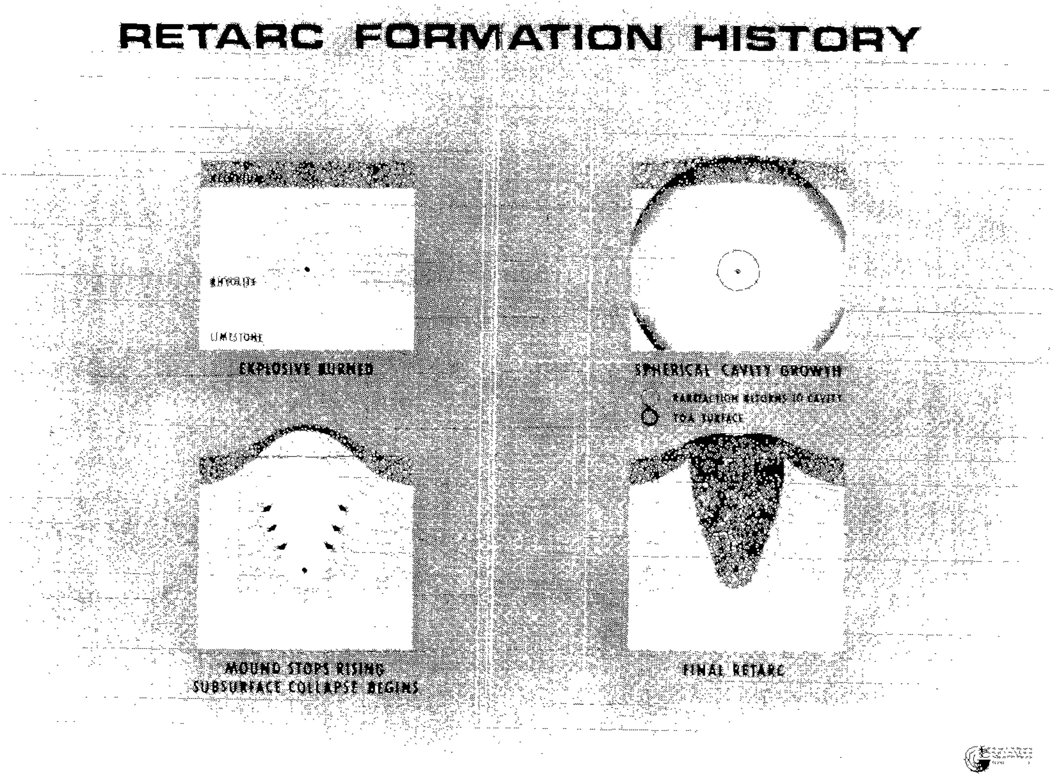

Fig. 9. Retarc formation history.

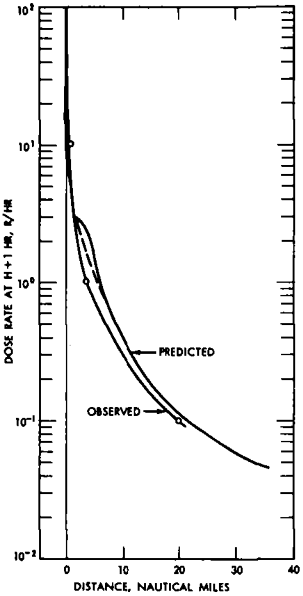

Fig. 10. Calculated and observed gamma dose rates at H + 1 hr as a function of distance along the "hot line" of the Danny Boy pattern (diagnostic calculation).

QUESTIONS FOR JOSEPH B. KNOX

1. From R. Cesped:

   Do the codes account for the effects of the natural angle of repose of the material in forming the dimensions of the apparent crater?

   ANSWER:

   No, the codes do not account for the natural angle of repose to be expected in the craters. Our calculations end at this time at two places: one, we either have the material in ballistic trajectory or else we have it in a two-dimensional hydro-code which is calculating the late-time mound growth during the time when all density changes are small--namely, during the gas acceleration phase and this code is known as MAC. We do not have a quantitative collapse model that brings the zones back into the crater under gravity along with the collapsing sides and puts the material in, with the collapsing sides coming in and then the material from above coming in on top. This would be very nice. So what is done is to use engineering judgment about the angle of repose and, when the material which is in flight above the crater and falling back in as bulk, an appropriate angle of repose is used by the person placing the material back in the crater to arrive at crater dimensions.

2. From P. Smith:

   Have the boundary conditions been calculated considering two vertically aligned shots at different ground depths in the case of sequential or simultaneous detonations?

   ANSWER:

   Well, let us put it this way, I'll answer it from the point of view of our laboratory in that others in the room may have done it. We have not calculated, to my knowledge, two simultaneously detonated explosives in a vertical hole. We have calculated three simultaneously detonated explosives, the same distance beneath the surface of the earth in a horizontal plan. In principle I believe we can do it, but we haven't done it.

UNDERGROUND ENGINEERING APPLICATIONS*

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ABSTRACT

Developments of any underground engineering application utilizing nuclear explosives involve answering the same questions one encounters in any new area of technology: What are the characteristics of the new tool? How is it applicable to the job to be done? Is it safe to use? and, most importantly, is its use economically acceptable? The many facets of the answers to these questions will be explored. The general types of application presently under consideration will also be reviewed, with particular emphasis on those specific projects actively being worked on by commercial interests and by the U. S. Atomic Energy Commission.

INTRODUCTION

Underground Engineering Application is the name that has been given to the group of Plowshare industrial uses that utilize the results of a completely contained nuclear explosion. In this paper we will discuss the nature of this new industrial tool, the types of uses that have been suggested and are under study, the general nature of the safety problems associated with these uses, and what economic factors must be considered. We will also discuss the specifics of several underground engineering applications currently under development.

CHARACTERISTICS OF THIS NEW TOOL

When a nuclear explosive is detonated underground, the initial result is the release of all of its energy and a large number of neutrons in less than a microsecond into the few tons of material comprising the explosive canister and the surrounding rock.

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*This work was performed under the auspices of the U. S. Atomic Energy Commission.

The neutrons are thermalized and captured in the material producing a variety of new nuclides, some of which are stable and some of which are radioactive with a variety of half-lives ranging from seconds to thousands of years. Deposition of such a large quantity of energy in such short time results in a spherical mass of material having temperatures of over ten million degrees and pressures of over one million atmospheres. At these temperatures and pressures, all of the material behaves like a gas or fluid.

In response to these pressures, the cavity filled with gaseous rock begins to rapidly expand against the surrounding medium, initiating an outward moving spherical shock wave. Figure 1 shows the various steps in the explosion process for a 5-kiloton explosion in granite. Initially, this shock wave is sufficiently intense to vaporize additional rock and add its mass and volume to the cavity. As the shock wave continues to expand, it is reduced in intensity and when it is no longer strong enough to vaporize the rock, it breaks away from the cavity and travels away from the cavity out into the rock (See <1 msec. in Figure 1). While it is still near the cavity, the shock wave crushes the rock as it stresses it beyond compressive strength limit. As the shock wave continues beyond, it continues to produce fractures in the rock, but to a reduced degree until the fracture limit is reached, beyond which the medium behaves elastically in response to the pressure wave. These steps are depicted as 3 msec. and 50 msec. in Figure 1.

The cavity continues to expand spherically until equillibrium is established between the pressure of the vaporized rock and water inside the cavity and the stress field in the rock. The cavity thus produced may stand for a period of time ranging from seconds to hours or days depending upon the type of rock, the depth of burial, and the explosive yield. When and if collapse occurs, the collapse will generally progress upward at about the same diameter as the cavity until the limit of the fracture zone is reached as indicated in Figure 1. The original volume of the cavity is thus redistributed as interstitial volume within the broken rubble filling the cavity or in apical void at the top of the zone of broken rock. In some materials, the collapsed material may increase in volume so greatly as a result of collapse that it will "use up" all of the cavity volume created and collapse will stop before it reaches the fracture limit.

Figure 2 illustrates the range of effects that have been observed as a result of varying the depth of burst. All experience has been depicted in terms of a 30-kiloton explosion in Lewis shale. Also shown in Figure 2 are the two possible results that may occur when the depth of burst is extended beyond 12,000 feet.

Figure 3 illustrates the range of effect that has been observed in four different geologic media. All this experience has been depicted in terms of a 30-kiloton explosion. As indicated, the size of the fracture zone and the probability and height of cavity collapse is very much a function of properties of the medium.

This rubble-filled, cylindrical volume is called a "chimney". For a 30-kiloton explosion, the diameter of the cavity and chimney range from

80 to 200 feet with the height to diameter ratio ranging from 1 to 3. Surrounding the chimney is a spherical fracture zone centered on the detonation point having about 3 to 6 times the cavity diameter. This, then, is the basic structure to be utilized in Underground Engineering Applications.

TYPES OF USES UNDER STUDY

Hydrocarbon Applications

A wide variety of Underground Engineering Applications deal with the production or use of hydrocarbons. As the energy requirements of our modern society expand at an ever increasing rate, our requirements for gas and oil will grow at such a rate that new resources and development techniques must be found. Plowshare Underground Engineering techniques appear to be applicable in a number of areas.

Gas and Oil Stimulation

The rate at which gas or oil can be produced from an underground formation or reservoir is directly proportioned to the effective permeability of the medium, and to the logarithm of the well diameter. Many fields have been discovered in which very large quantities of gas and oil are present but cannot be removed in an economically feasible manner because the permeability is too low.

For this application, illustrated in Figure 4, the highly permeable rubble-filled chimney plays the role of a greatly increased well bore. To the extent that the fractures surrounding the chimney and detonation point are permeable, they will further extend the effective radius of the well bore. Thus, creation of such a chimney and fracture system in a gas or oil reservoir that contains a large quantity of hydrocarbons, but is not permeable enough to allow them to be economically produced, will greatly stimulate the rate of production and increase the production of the in-place reserves that can be recovered through a single hole. Estimates of the degree of stimulation prior to the first stimulation experiment, Project Gasbuggy, ranged from 3 to 6. The results of Gasbuggy as well as plans for future experiments are discussed below.

In-situ Oil Shale Retorting

Several basins in Western Colorado, Utah, and Wyoming contain tremendous deposits of oil shale. The U. S. Bureau of Mines has estimated that the reserves in the Piceance Creek Basin of Colorado alone represent 320 billion barrels of oil which is about four times the present U. S. recoverable petroleum reserves. Oil shale consists of a marlstone which contains a hydrocarbon called kerogen. When heated to about 650°F, the kerogen undergoes chemical decomposition into various gaseous hydrocarbons including oil and gas vapor leaving a residue of carbon.

The nuclear application envisages the detonation of a nuclear explosive at the base of the oil shale formation, creating a large chimney filled with broken oil shale (See Figure 5). Combustion would then be started at the top of the chimney and sustained by air pumped in from the surface. By drilling several holes to intersect the base of the chimney, a circulatory system can be established in which air is pumped in at the top of the chimney to support the combustion front consuming the residual carbon. The hot combustion products would then be swept ahead to heat and retort the raw shale lower down in the chimney and ultimately to mix with the vaporized hydrocarbons and be pumped to the surface for separation. This cycle is shown in Figure 5 together with a demonstration of how a multiple array could be used to retort the oil shale between chimneys.

Major questions that impact on the feasibility of this application are the probability of collapse at permissible yields, the size of the particles in the chimney, and the efficiency of the retorting process. Significant work on the latter question is being done by the Bureau of Mines at their Laramie Research Station in a retorting facility capable of retorting 10 tons of shale at a time.

Gas Storage

Over the last 20 years there has been a tremendous growth in the use of natural gas as an energy source. There is every indication that this growth rate will continue at the same or increased rate. The major problem facing the gas distribution industry today is the tremendous fluctuation in demand for gas from week to week and month to month. In order to avoid having to build pipeline facilities as large as peak demand requires, various means of storing gas near the consuming market to meet peak demands have been developed. The investment of the gas industry in storage facilities to date is over one billion dollars. Most storage has been provided through the use of depleted oil and gas formations. These have the advantage of very low cost to develop and maintain, but the rate at which the gas can be removed is limited. Unfortunately, because of the growth of the gas industry, virtually all known depleted formations are presently being used. The other principal means of storage is liquefication and pressurization. This means has high "deliverability" but is much more expensive to build and operate.

The Plowshare application in the gas storage industry envisages creating a chimney in a very tight, unfractured, impermeable formation such as shale or salt and at a location as close to the market as seismically acceptable, and pumping it full of gas. Pressures as high as lithostatic may be used. The volume used is in the interstices between the rubble fragments and in the fractures extending out to several cavity radii from the cavity. Because of the very great permeability of the chimneys, the deliverability of the chimney is limited only by the size of pipe to the surface. Two independent studies of this application have shown that 50- to 100-kiloton chimneys would be very competitive economically with the other means of storage and have the added advantage of very high deliverability.

Petroleum Storage

Nuclear chimneys can also be used for the storage of petroleum in an application very similar to gas storage discussed above. Such a use appears particularly attractive for off-shore drilling situations or in the Arctic where it is necessary to stockpile petroleum while awaiting the arrival of periodic tankers. A 100-kiloton chimney at a depth of 3,000 feet would produce over 2 x 10^6 bbls of storage at a capital cost of between 1 and 3 dollars/bbl.

As for gas storage, an impermeable formation would be required for petroleum storage in which fractures emanating from the chimney would terminate before they encountered an extensive fracture system or ground water.

APPLICATION IN THE MINING INDUSTRY

In-situ Copper Leaching

Another application of Plowshare Underground Engineering which appears to have great promise is the in-situ leaching of copper ore from low-grade ore deposits. Throughout the southwest U. S. a large number of low-grade copper ore deposits exist which contain large quantities of copper, but in which the copper is so diffusely distributed that it is not economical to remove the copper by conventional block cave mining or by over burden removable and open pit mining. For those deposits which are sufficiently deep, the application shown in Figure 6 would involve creating a chimney in the ore deposit followed by the introduction of an acid solution at the top of the chimney. As the solution percolates downward through the broken ore, copper would be leached from the new surfaces as well as from those fractures accessible to the leaching solution within the rock. The pregnant liquor would be recovered at the bottom of the chimney and pumped to the surface where conventional separation facilities would remove the copper and return the acid to the top of the chimney for another cycle.

Two methods of recovery are available. One is illustrated in Figure 6, in which drill holes from the surface have been whipstocked into the lower chimney region. Down hole pumps would be installed and used to pump solution to the surface. Alternatively, a shaft and tunnel below the chimney with collection galleries radiating from the tunnel could be used.

A variation of this technique applicable to very shallow low-grade ore deposits or ones which extend to the surface is illustrated in Figure 7. For this application, the depth of burial and yield are chosen such that the dynamic effects of the explosion reach the surface of the ground, but do not produce a crater. At this depth of burial, a structure called a retarc is formed which is halfway between a crater and a chimney and has the shape illustrated in Figure 7. The application is envisioned to involve spraying leaching solution on the surface of the retarc, recovery of the pregnant solution at the bottom of the retarcs through a hole or shaft and tunnel, followed by conventional separation.

One of the major problems of the in-situ copper leaching application is quite obviously the efficiency of collection of the pregnant solution. The other major question is the efficiency with which the minerals can be removed from the broken rock by in-situ leaching.

The methods described above may be applicable to other minerals providing economical leaching techniques are available. Mineral deposits which are too deep for manned recovery because of the high temperature are particularly suitable as well as the recovery of such products as salt and sulphur.

Block Cave Mining

Reentry to the chimney by means of shaft and tunnel could also be used for the removal of ore deposits through the use of block cave mining techniques quite analogous to those currently in use in the mining industry. The advantage of the chimney would be that the rock would be fractured before block cave mining was attempted. Such a technique would be most applicable to ores such as taconite, which are so strong that conventional block cave mining techniques are not practical. An additional advantage of such a technique would be that the breakage of the ore would probably be enhanced over that obtained by conventional block cave mining methods.

THE NATURE OF THE SAFETY PROBLEM

For Underground Engineering Applications, the principal safety problems can be resolved into two categories, ground motion and radioactivity.

Radioactivity

The radiation safety problem can be broken down into three parts: off-site safety of the general public surrounding the project; on-site or industrial safety of project or company personnel; and safety of the general public from product contamination. I will only lightly touch on each of these areas to put them in perspective and later papers will discuss them in much more detail.

Radioactivity is produced from three sources:

1. Fission of nuclear materials which produces a wide variety of fission products radionuclides including both gaseous and refractory elements;

2. Tritium and beryllium produced by any thermonuclear actions involved in the energy source;

3. Radioactive nuclides produced by neutrons from the explosive in the components of the explosive and the surrounding environment including any casing or grout material.

For applications involving hydrocarbons, the most severe problem is associated with tritium which can be produced in a thermonuclear reaction or by interaction of neutrons with lithium in the rock. Because tritium is an isotope of hydrogen, it behaves chemically like hydrogen and exchanges with hydrogen atoms in hydrocarbons and water. The rate at which this exchange takes place is a function of the temperature and pressure in the chimney. Once the tritium exchanges with the hydrogen, it is virtually impossible to separate the tirtium from the hydrocarbon and dilution is the only means of reducing the level of tritium contamination. For this reason, hydrocarbon applications require the use of all fission nuclear explosives and sufficient shielding to reduce the production of tritium in the soil to a level at which the produced contamination is acceptable. For hydrocarbon storage, flushing of the chimney with air or water would be very effective at reducing the background level of gaseous radioactivity and would minimize contamination of any hydrocarbon stored in the chimney.

The only fission product of concern for gas stimulation and gas storage is krypton-85, a noble gas. If the contamination by this isotope is unacceptably high, it can be removed by existing techniques.

For non-hydrocarbon applications such as <u>in-situ</u> leaching of copper, the hazard from tritium will be confined to the industrial hazard within the separation or processing plant. Product contamination will involve only those nuclides which are dissolved by the leaching solution and are chemically similar to copper. Preliminary studies have indicated that ruthenium is the only fission product that shows any tendency to follow copper. The extent of any such problem must be evaluated in an actual experiment. Conventional electrolytic refining of the copper would remove even the ruthenium.

The block cave mining applications or shaft and tunnel collection in connection with <u>in-situ</u> leaching must recognize problems of tritium contaminated water vapor which would constitute an industrial safety problem.

Off-site hazards from radioactivity can occur at the time of the detonation and during the chimney reentry and product recovery phases.

In general, the great depth of the Underground Engineering Applications reduces the probability of escapes of radioactivity at the time of the detonation to an extremely small number. Great care must nevertheless be taken in planning and executing these events to avoid the chance of off-site exposure.

Ground Motion

For almost all Underground Engineering Applications, the primary off-site safety problem arises from ground motion experienced by surrounding communities as a result of the nuclear explosion. This problem can be resolved into three parts: the nature of the source and the material surrounding it; the nature of the material in the transmission path between the source and structures of concern; and the characteristics of the structure and the nature of the material on which it is built. Experience has shown that the probability of damage of structures can be related to the motion they experience. The type of damage most frequently involved in Plowshare Underground Engineering Applications is expected to be architectural, and not structural. Nevertheless, such damage represents real costs and must be taken into account in the planning of any Plowshare experiment.

ECONOMICS

The cost of any Plowshare Underground Engineering Application involves three factors. First is the cost of the nuclear explosive and its detonation. Figure 8 gives a summary of the explosive service charges published by the Atomic Energy Commission that are recommended for planning purposes in evaluating Plowshare applications. These charges include the cost of the nuclear explosive, its transportation to the detonation site, and its detonation, but do not include such costs as the emplacement hole, stemming, cabling, and all other support requirements.

The second major cost items are those associated with emplacement of the explosive, stemming, cabling, providing vehicular and construction support and logistics. These costs can vary quite widely depending on the depth of burial, the geological locations, and the size of the emplacement hole required.

The third major category of costs are those associated with the industrial utilization of the chimney. Involved here would be holes drilled to recover the product, surface installations of product processing and refining, and radiation monitor and control of decontamination facilities.

Because of the interaction of radioactivity production with explosive cost, diameter, and decontamination facilities required, these three cost items are intimately related to one another and must be considered together to realize a minimum cost for an application.

CURRENTLY ACTIVE PROJECTS

Figure 9 summarizes the location of those projects which are under active consideration by the Atomic Energy Commission at the present time.

Included here is the Gasbuggy experiment which is undergoing production tests at the present time. In the Gasbuggy experiment, a 25-kiloton nuclear explosion was detonated at a depth of 4,240 feet in a low permeability gas reservoir in northwest New Mexico in December, 1967. To date, in excess of 167 million cubic feet of gas have been recovered from the Gasbuggy chimney. Production from an existing gas well about 400 feet away over a nine-year period has totaled about 85 million cubic feet. The gas produced has been flared and has not constituted a hazard to test personnel or to the general public off the site. Production tests are continuing to provide definitive data with which to evaluate the degree of stimulation of the formation but initial results are quite favorable.

Rulison

The Rulison experiment, which has been proposed by the Austral Oil Company and the CER Geonuclear Corporation is a gas stimulation experiment planned for execution in the spring of 1969 which has been designed to investigate the commercial feasibility of gas stimulation in the Rulison Gas Field in western Colorado. It will involve the detonation of a 40-kiloton nuclear explosive at a depth of about 8,430 feet, reentry of the chimney, and production of gas. A contract between the Federal Government and Austral/CER was recently signed for carrying out the project. Under the terms of this contract, Austral will provide all work and services for the project except the nuclear explosive and related services such as firing the explosive and direction of nuclear operational safety procedures.

Dragon Trail

Dragon Trail is a gas stimulation experiment proposed by the Continental Oil Company and the CER Geonuclear Corporation involving the use of a nominal 20-kiloton nuclear explosive in a gas reservoir formation about 16 miles south of Rangely, Colorado. The depth of burial of this experiment is about 3,000 feet. Plans are currently being developed for the experiment and a detonation in fall or early winter of 1969 is anticipated.

WASP/Pinedale

Two experiments, WASP and Pinedale, have been proposed for a deep, low permeability gas reservoir in the Pinedale basin north of Green River, Wyoming. International Nuclear Corporation, representing a group of six companies has proposed a detonation of a nuclear explosive in the range of 50-kilotons at a depth of approximately 11,000 to 12,000 feet. The El Paso Natural Gas Company has proposed a similar event at a nearby location in the same Green River basin. This reservoir extends from 10,000 feet to as deep as 18,000 feet and introduces a new realm of temperature and pressure problems associated with these great depths. However, the high pressures also mean that large quantities of gas are present and so the economic incentive for its recovery is great. For this reason, the technical problems associated with the emplacement of a nuclear explosive, the creation of a chimney, the establishment of a fracture system, and the production of gas from this environment must be faced. These projects are in the early stage of development and will not involve detonations for several years.

Sloop

Sloop is an in-situ copper ore leaching experiment proposed by the Kennecott Copper Corporation for an ore deposit located about nine miles northeast of Safford, Arizona. The experiment would involve a 20-kiloton nuclear explosive buried at a depth of 1,200 feet at the base of a low-grade copper ore deposit. This experiment is under active development and planning at the present time and a detonation the late spring or summer of 1970 is anticipated.

Ketch

In the fall of 1967, the Columbia Gas System Company proposed a joint industry-government experiment to explore the possibility of using nuclear explosives to produce underground gas storage facilities. A 24-kiloton experiment, named Project Ketch, was proposed. At the present time, the company is considering three locations in the middle Atlantic states as indicated in Figure 9.

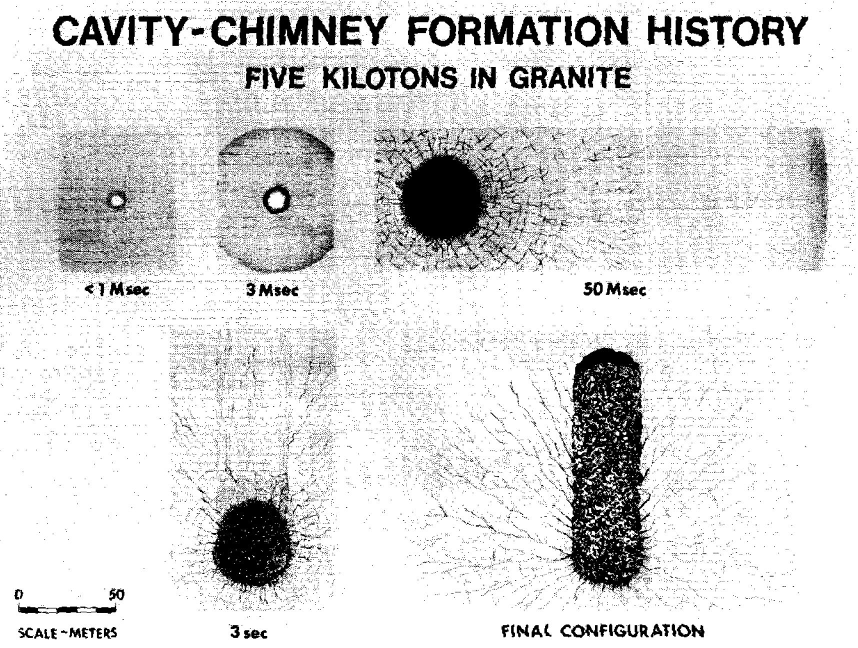

Figure 1 - Cavity-Chimney Formation History

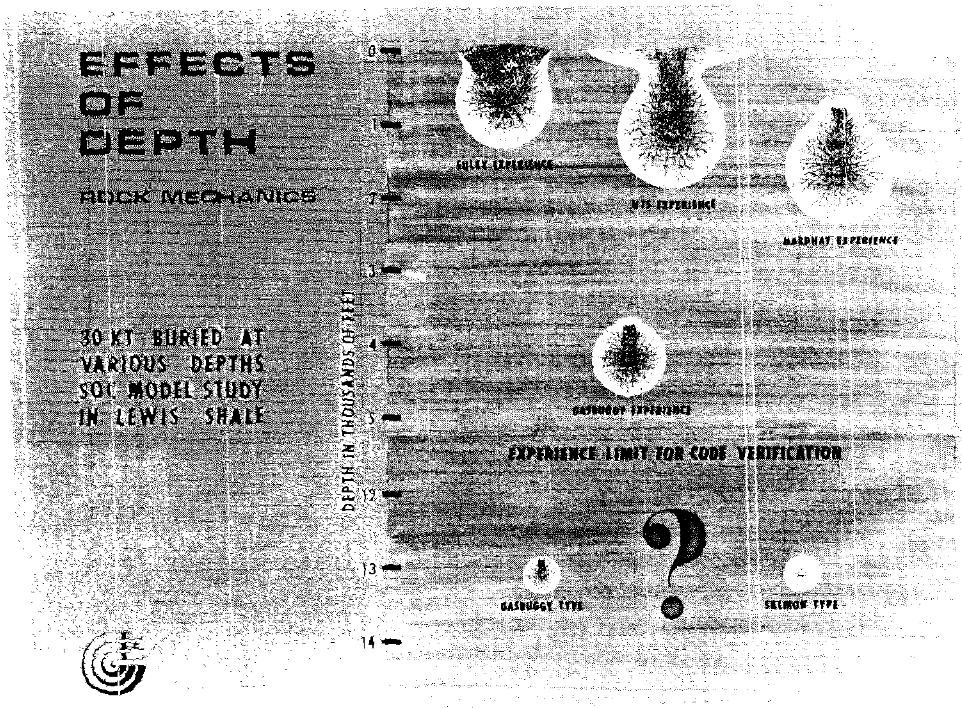

Figure 2 - Effects of Depth of Burst

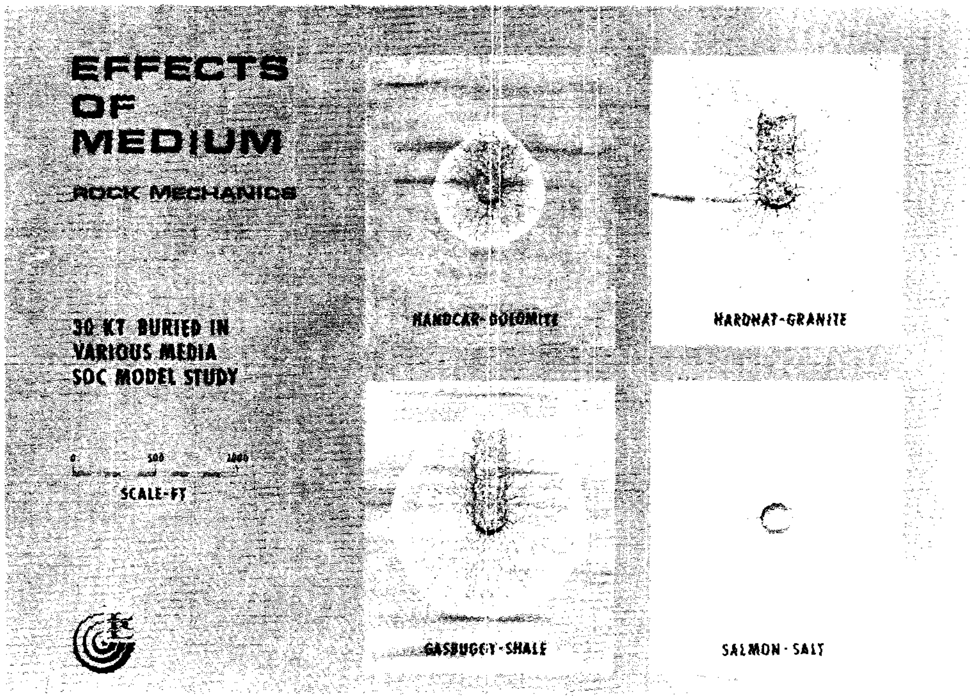

Figure 3 - Effects of Medium

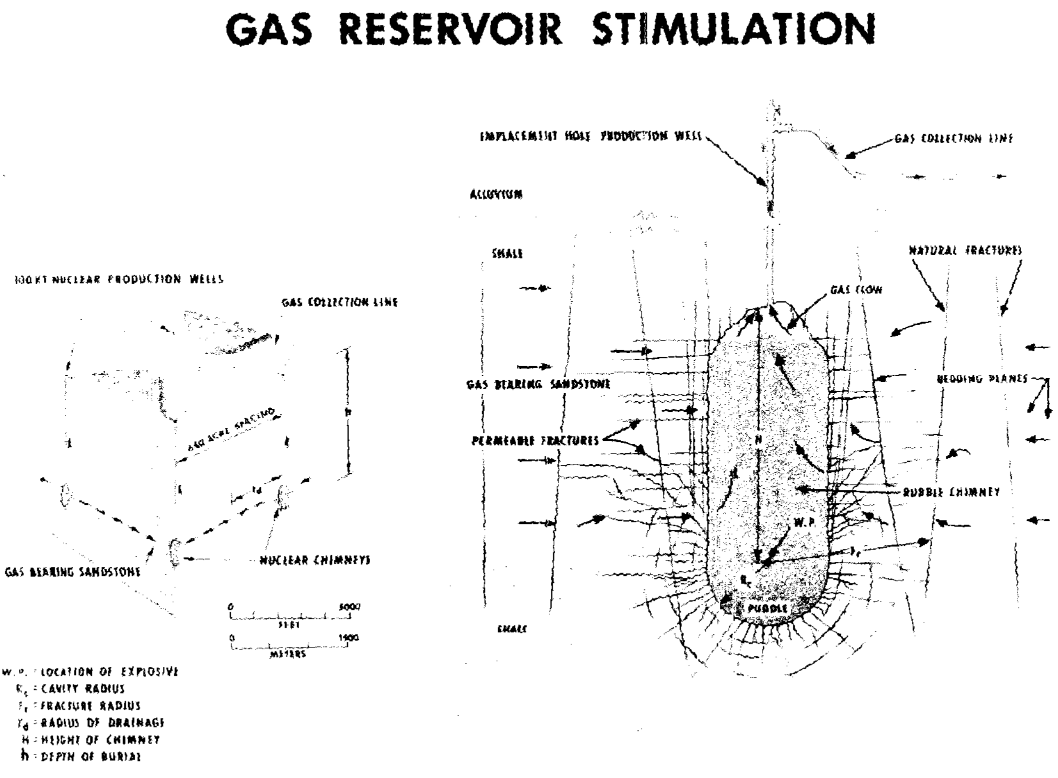

Figure 4 - Gas Reservoir
Stimulation

IN-SITU RETORTING-OIL SHALE

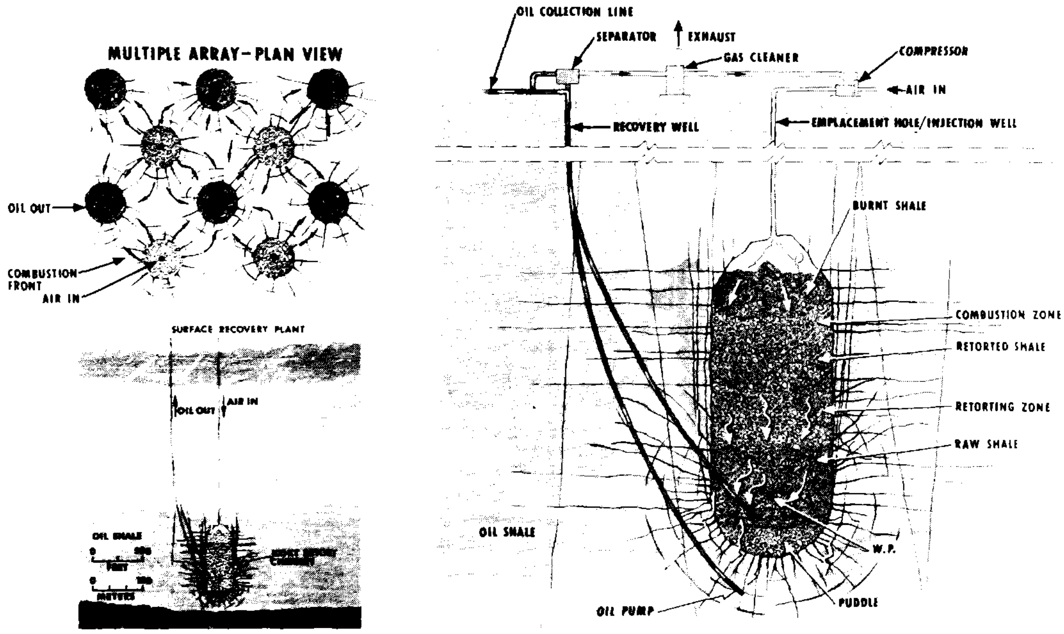

Figure 5 - In-Situ Retorting-Oil
Shale

IN-SITU ORE LEACHING

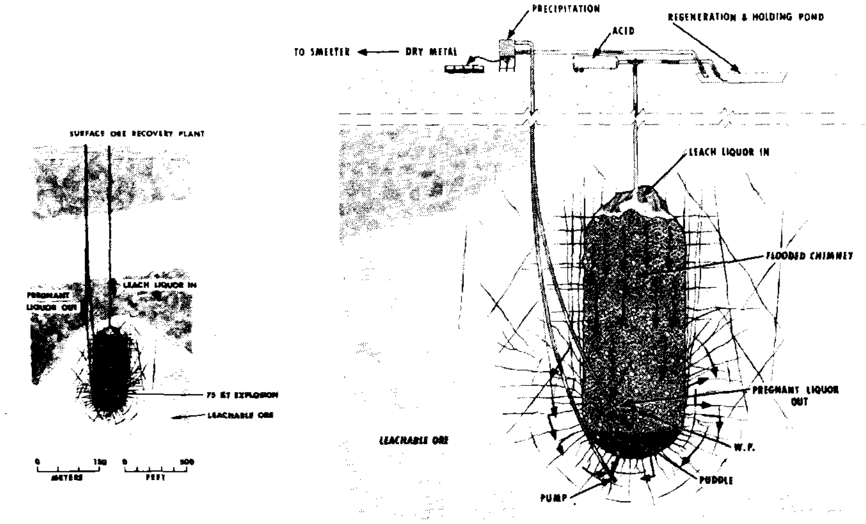

Figure 6 - In-Situ Ore Leaching

RETARCS FOR IN-SITU LEACHING

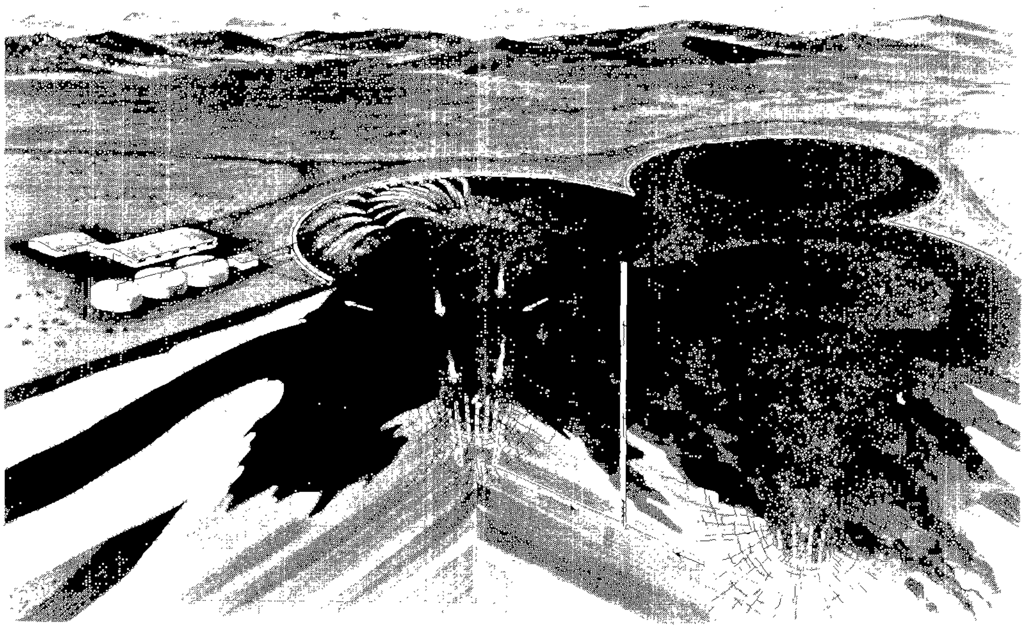

Figure 7 - Retarcs for In-Situ Leaching

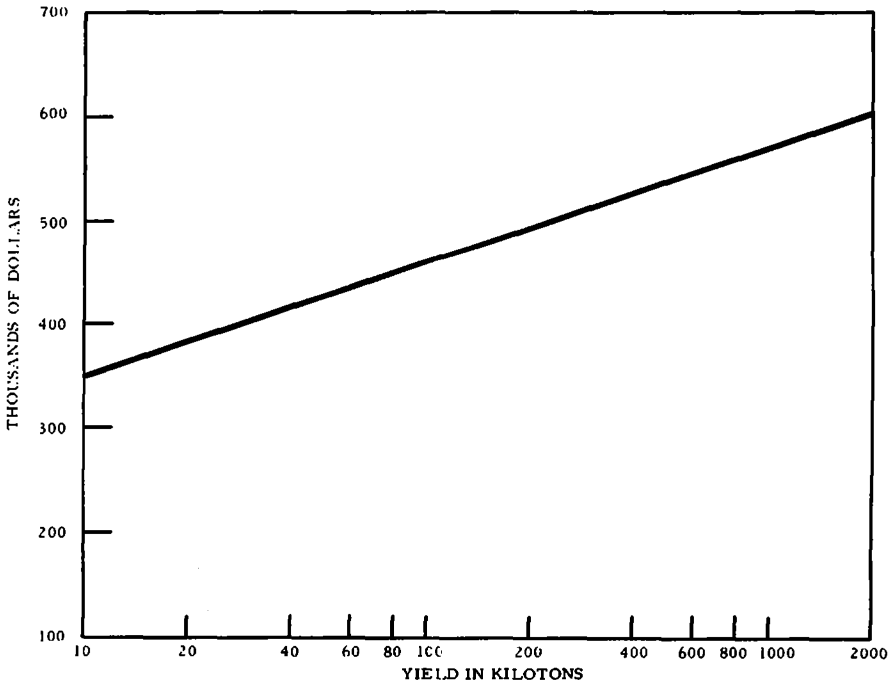

Figure 8 - Schedule of Projected Nuclear Explosion Charges

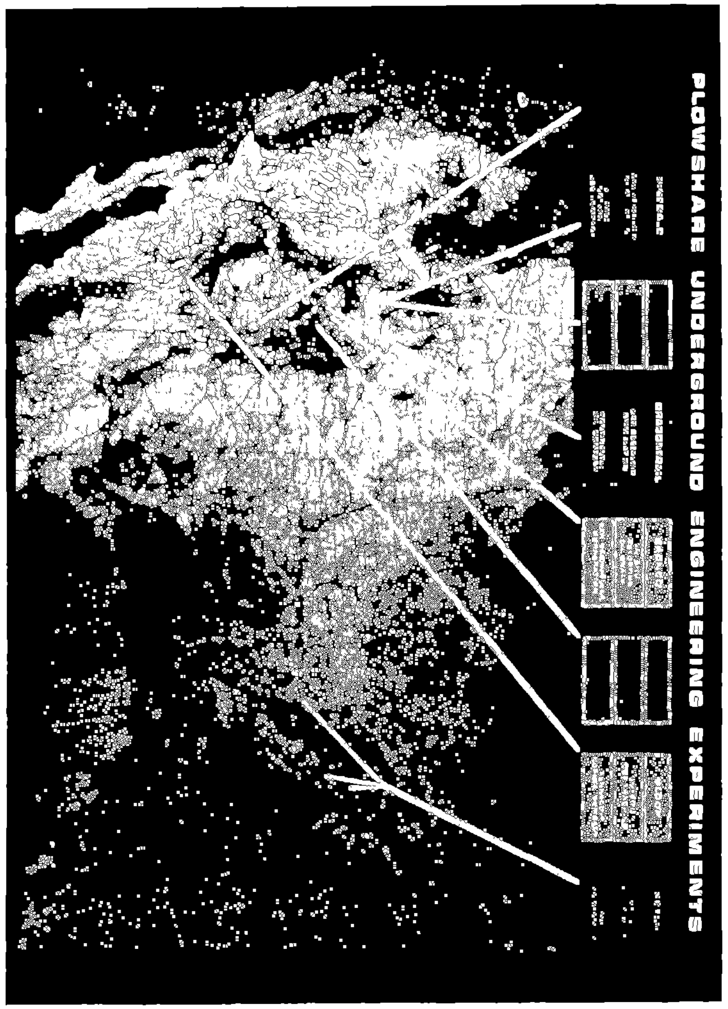

Figure 9 - Plowshare Underground
Engineering Experiments

QUESTIONS FOR MILO NORDYKE

1. From D. Harward:

I understood you to say that the chimney could be flushed to remove radionuclides. Would you please explain this in more detail?

ANSWER:

Well, it depends on the application and the type of chimney, but in a storage application where you have a presumedly tight chimney, you have to maintain first of all if you are going to flush it with a fluid or gas, one would have to establish a circulation system in which you pump in air or gas, but presumedly air, at the bottom and remove gas at the top and by pumping in several chimney volumes by this technique, one can remove the--or reduce the contamination level by--between one and two orders of magnitudes. I am speaking particularly with respect to tritium which is of course soluble in water. It ends up as a chemical condition of water. In the case of fluids, in the case of copper leach, the first solution one can put into the chimney is just plain water which would flood the chimney and the tritium, which has a great affinity for water and would follow the water down, can be pumped out at the top. Again, similar to the copper leach application in which you introduce liquor, but in this case you just introduce water, and remove the first chimney-full volume of water and most of the tritium with it.

2. From C. F. Harris:

What information has been obtained in gas stimulation experiments pertaining to any contamination of underground water supplies?

ANSWER:

Well, I think we haven't obtained any information in gas stimulation yet because we didn't penetrate to any underground water supply. We have constantly been concerned about the problem of contamination in an underground water supply. During Gnome, for example, we spent a great deal of time and money sampling the water aquifer which was 600 feet, I believe, above the shot point watching for nuclides introduced into the water by fractures from the shot point extending up that far. We had very negative results. But in the case of Gasbuggy, we have not seen any fractures extending to an aquifer and certainly have not seen any radioactivity in the aquifer. Dr. Holzer is going to describe some of the results from Gasbuggy and can speak to that more fully.

DR. HOLZER:

There is now a book by the U. S. Geological Survey on the geology and hydrology of the Nevada Test Site in which considerations of ground water migration and distribution coefficients, the kind of things one must look for in water, are treated quite lucidly and I might say that to my knowledge at least there has not been any documented evidence of any ground water contamination from nuclear detonations.

SUMMARY OF RESULTS OF UNDERGROUND ENGINEERING EXPERIENCE[*]

Fred Holzer
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ABSTRACT

Results pertinent to the use of nuclear explosives in underground engineering applications have been accumulating for the past 10 years from the Plowshare and Weapons tests of the AEC. Thus, predictive and measurement techniques of shock effects and chimney formation were developed in the course of analyzing explosions in granite, salt, and dolomite. The ability to predict effects related specifically to safety has resulted from many measurements on detonations at the Nevada Test Site, where also many of the techniques for handling, emplacing, and firing the explosive have been developed.

This gestation period culminated in the execution of Project Gasbuggy, jointly sponsored by industry and government, and the first nuclear explosion in a gas-bearing formation. The Gasbuggy explosive had a nominal yield of 25 kt and was detonated 4240 ft below the surface in the San Juan Basin in northwestern New Mexico on December 10, 1967. The shot point was 40 ft below the lower boundary of a 285-ft-thick gas-bearing sandstone formation of very low permeability. No radioactive venting occurred, and no damage to surrounding gas wells or structures resulted. Post-shot geophysical exploration and gas production tests have revealed that the nuclear explosion created a subsurface chimney approximately 160 ft in diameter and 335 ft high. Fractures appear to extend to about 400 ft symmetrically from the detonation point, with shifts or offsets along geological weaknesses extending out to perhaps 750 ft. Presently, radioactive constituents in the gas consist of tritium and krypton-85, with concentrations of approximately 10 $\mu Ci/ft^3$ and 1.5 $\mu Ci/ft^3$ respectively. These concentrations are decreasing as gas withdrawn from the chimney is replaced by formation gas. Tests to evaluate the increase in productivity and ultimate recovery are currently in progress.

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[*] *Work performed under the auspices of the U.S. Atomic Energy Commission.*

Results from underground nuclear detonations have accumulated ever since the first underground detonation in 1957. As the number of media in which nuclear explosions took place increased, data from these explosions could be put within the framework of a developing theory in which differences between these various detonation effects became meaningful. In turn, the growing body of theory and computation could be used to predict in an increasingly reliable way the effects of new underground detonations. In treating these various effects, it was found convenient to separate effects either spatially according to the region in which they occur, or in time according to the periods after the detonation where the various effects predominate. Thus, early in our experience we talked about close-in effects, meaning the effects of the shock wave, the growing of the cavity, as well as the manifestations of the detonation at or near surface zero. The general generation of the seismic wave and its propagation to distances where its effect is important is an early or prompt manifestation of the detonation. Effects and results from underground detonations stretch in space from the very high pressure hydrodynamic region close to the detonation all the way to the seismometer on the other side of the world and in time to the generation of the shock wave with the release of energy at the explosive to the release of radioactive gases perhaps many months afterwards during a reentry or gas production phase of the experiment. Here, however, I shall limit myself to two areas of effects from detonations which are of special interest to the field of underground engineering applications. Of central importance in these applications are the area of the subsurface chimney and the region of rock immediately surrounding this chimney. I will attempt to relate some of the things we know about these regions, using the results from the Gasbuggy experiment as a case study. The second area of special interest to the underground engineering area in general and to this group in particular is the composition of the gases one can expect to find in the chimneys of underground detonations, in particular from detonations in a gas reservoir. In this latter case, results from Gasbuggy of course are the only ones available at this time.

For underground engineering applications, the region surrounding the detonation center and including the chimney and the fractured region is of primary importance to the application. Thus, in the attempt to stimulate gas reservoirs, the chimney and fracture regions serve as the gathering system for the natural gas, and it is the increased permeability of these regions over the natural state in which the utility of these nuclear explosions lies. In the case of oil or gas storage, the void space of the initial cavity is distributed throughout the chimney as interstitial porosity and represents the economic benefit of the explosion in this particular application. In the area of mining, the diminuted rock which is distributed as rubble within the chimney represents the end product. In the case of an in situ leaching application, it is again the rubble within the chimney which makes the leaching application possible. What then do we know about the cavity, chimney, and fractured region surrounding underground detonations? Actually, we know quite a bit. In practice we will need to know a lot more. We have, for example, a considerable amount of data on cavity sizes from the weapons tests in alluvium and tuff at the Nevada Test Site.[1] We have a great deal less information about chimney sizes from these detonations, since most of them have resulted in subsidence craters where the chimney goes all the way to the surface. For those that have formed chimneys contained below the surface, we have only fragmentary information about such chimney sizes.[2] Aside from these detonations in volcanic rocks we have data from three detonations in granite,[2] two detonations in salt,[2] one in dolomite,[3] and one in sandstone and shale, namely Gasbuggy. Attempts to systematize data on cavity sizes using a thermodynamic approach were first published by Boardman et al.[2] Later, Higgins and Butkovich[1] used thermodynamic properties of rock vapor to derive the values of the purely empirical constants appearing in Boardman's equation. In this approach the cavity is allowed to expand from its initial vaporized size until the pressure is equal to the lithostatic overburden. The result of this procedure is shown in Fig. 1. No chimney height information is contained in this procedure. Chimney heights were usually approximated to be about 4 or 5 times larger than in the cavity radii.

A second technique, developed by Cherry et al.,[4] makes use of a computer calculation and measured strength properties of the rock. Cavity sizes are calculated by hydrodynamic-plastic-elastic computer calculations using measured rock properties. Chimney heights result from comparing the amplitude of the outgoing stress wave with the strength property of the rock to determine the radius of failure of this rock. While chimney heights are not directly calculated by this method, experience has shown that predicted failure radii are within 15 percent of observed chimney heights. In this procedure failure radii of chimney heights are not directly tied in to cavity radii, but are primarily governed by the rate of stress wave decay and rock strengths. Figure 2 graphically compares predicted and measured cavity and failure radii for the 12-kt Handcar explosion in dolomite and the 5-kt Hardhat explosion in granite. The reasons for the smaller failure radius in Handcar can be attributed to the strength properties of dolomite and granite depicted by Fig. 3, which shows that in the low-stress region dolomite is stronger than granite.

This theory also predicts several additional consequences. The first concerns the geometry of the failed region. Since the outgoing stress wave is spherically symmetric, one could expect a failure region whose surface is that of a sphere surrounding the detonation, and whose radius then is approximated by the chimney heights. If indeed rock is failed below the detonation center as well as above, the vertical extent of rock failure is effectively twice the chimney height, and the ability of a nuclear detonation to stimulate reservoirs would be very much enhanced over what it had been thought to be previously. The theory also predicts that for deeper detonations where the overburden causes the rock to behave more ductile than at shallower depths, the cavity and the failure region produced could be significantly reduced.[5] Since we have no experimental verification or indeed any experience at a depth in excess of about 4500 ft, these predictions must be verified by future experiments.

Let me now describe what we know about the Gasbuggy cavity and chimney region, and how they compare with our preshot expectation.[6] The nominally 26-kt Gasbuggy explosion was detonated 4240 ft below the surface. The shot point was in the Lewis Shale formation some 40 ft below its contact with the Pictured Cliffs sandstone. This formation, about 300 ft thick, is in itself non-uniform and is overlain by a 40-ft section of coal which is of low density and highly fractured. The geology cross section is shown in Fig. 4, and it is apparent that a calculation of failure radii must take account of the physical properties of the different layers involved. A layered geology such as is exhibited here, and one that is typical of geologies of sedimentary basins makes it difficult to apply an empirical procedure in the prediction of cavity and fracture region sizes; for Gasbuggy, the calculational failure radii model was used. A cavity radius of 78 ft was predicted. The difference in physical properties gave an expected failure radius vertically above the shot point of about 335 ft, a failure radius within the Pictured Cliffs sandstone of about 400 ft and a failure radius within the Lewis Shale of about 500 ft.[7] We also recognized before the shot that the various bedding planes formed primarily by coal seams might exhibit offsets to larger distances than those calculated for the homogeneous rock. Such did turn out to be the case. The inclusion of such weaknesses in a failure prediction is one of the tasks of the future. Figure 5 shows the state of our knowledge of the Gasbuggy chimney. The information was obtained from geophysical exploration in the reentry hole to the top of the chimney,[8] prompt information from the fracture cable system which was emplaced in hole GB-1 about 150 ft away from the emplacement hole,[9] and geophysical exploration of the reentered GB-2 hole to a depth of 4600 ft.[10] Information on cavity volume comes from the analysis of the short-term gas flow tests performed during June and July 1968.[11] Here the void volume is calculated by noting the amount of pressure decrease for a given volume of gas withdrawn. This void volume for Gasbuggy amounts to approximately 2 million ft^3, and is equivalent to a sphere of 80-ft radius. The chimney height shown in the figure represents the location of a void carrying both gas and radioactivity which was encountered during reentry drilling at a depth of 3907 ft below the surface. Upon closer examination of the data, offsets and casing breaks in the emplacement hole were identified as having occurred between 3800 ft and the chimney top at 3907 ft. These casing breaks can be correlated with bedding plane weaknesses noted during the coring and logging program of the GB-1 preshot hole. The locations of those fractures are also corroborated by the failures in the fracture cable system installed in GB-1 which are also shown in this figure. Figure 6 shows some of the results obtained during the reentry of the GB-2 hole located approximately 300 ft away from the emplacement hole. During this reentry, offset casing was encountered 3812 ft below surface or almost 630 ft from the shot point. This offset casing necessitated sidetracking the hole, after which it was drilled and completed to 4600 ft. The preshot hole, GB-2, was drilled through very competent rock, resulting in a very uniform diameter hole. Such was not the case for the sidetrack portion of the new hole. This figure shows results of two caliper logs run 35 hr apart, noting that the hole is very ragged and sluffs very readily. Figure 7 compares the porosities determined pre- and postshot in terms of porosity changes. While there is some scatter, it is obvious that in general the porosity has increased. Figure 8 presents the quantitative results on gas entries observed in this hole and compares them with some of the preshot numbers. Gas flow during drilling as shown by the left-hand portion of this figure had increased considerably over that found when the original GB-2 hole was drilled. Gas entry locations are determined by means of the temperature log shown and the Packer Flow meter which quantitatively determines the amount of gas flowing through the instrument at various depths. Of special interest here are the gas entries shown by both the temperature log and the Packer Flow meter in the Lewis Shale section below 4200 ft. Since the Lewis Shale does not contain any gas in this locality, the gas entries here are indicative of fractures communicating with the chimney, or at any rate with the Pictured Cliffs gas bearing formation above. This is the only evidence which we now have indicating the correctness of the failure radius concept and its importance in the gas stimulation area.

Of course the quantity of more direct interest is the increase in permeability of the rock with respect to its ability to transmit gas. In practical reservoir terms, we need to know the increase in productivity and recovery of the stimulated Gasbuggy reservoir. Figure 9 shows some of the data that are being taken to arrive at a solution to this problem. Shown here are the flow rates of gas from the Gasbuggy chimney which were found to be necessary in order to maintain the pressure at the top of the chimney at three different constant values. The reservoir engineers from the Bureau of Mines and the El Paso Natural Gas Company are in the process of anlayzing these data. It is interesting to note, however, that the total amount of gas withdrawn from the Gasbuggy chimney up to now is approximately 200 million $ft.^3$ Since being drilled in 1956, Well 10-36, the conventional well located some 415 ft from the Gasbuggy emplacement hole, has produced about 81 million ft^3 of gas. In fact, of the eight wells closest to Gasbuggy, only three had produced more gas than Gasbuggy has up to this time.[6] Another way to look at the 200 million ft^3 of gas produced would be to realize that that amount of gas is present within a cylinder 300 ft in radius in the Pictured Cliffs gas bearing formation at the Gasbuggy site.

The next set of figures will illustrate another major area of study of Gasbuggy, namely the composition of the gas, with emphasis on the concentration of radioactive constituents.[12] Particular attention has been paid to the gaseous isotopes krypton-85 and tritium, whose half-lives are 10.6 and 12.6 years respectively. They show, of course, very little reduction in amount due to natural decay. Iodine, a short-lived isotope, was not detected at Gasbuggy. The presence of iodine-131, while having no long-term significance, could make an early reentry operation expensive and inconvenient. The reason for the apparent retention of iodine underground is not very clear, although from the presence of xenon isotopes, we know that the iodine was produced. Figure 10 shows the results of sample analysis taken during the first six months after the detonation. The gradual decrease in tritiated hydrogen concentration may be due to the reaction of hydrogen with carbon dioxide to form methane and water. This is supported by Fig. 11 which shows the changes in chemical concentration of the gas over this same sampling interval. The salient features of both of the last two figures are the total concentration of tritiated gas of about 18 to 20 μCi/ft^3, a krypton-85 concentration of approximately 3 μCi/ft^3, and a CO_2 concentration of about 35 percent. While the tritium concentration is less than expected by perhaps a factor of 20, we did not anticipate finding such a large amount of CO_2. It has been proposed to decrease these concentrations by flaring chimney gas and replacing it with clean gas from the surrounding formation.

Figure 12 shows the analysis of samples taken during the June-July flow testing, when approximately 60 million ft^3 of gas were flared from the chimney. The marked decrease in concentrations taking place at about July 10 corresponds to a decrease in flow rate from 5 million ft^3 per day to three quarters of a million ft^3 per day. Such a decrease in concentrations is most likely explained by a change in the influx pattern of gas into the chimney. The corresponding change in the chemical constituents is shown in Fig. 13. Here the decrease in CO_2 and hydrogen is reflected by a corresponding increase in the hydrocarbon content of the gas.

Figure 14 shows the results of the continuing analysis of gas during the flow tests which started at the beginning of November. The gas withdrawal rates during this period are shown on the same graph for comparison. The corresponding amounts of the chemical constituents are shown on Figure 15. The changes in CO_2 concentrations with flow rates seem to follow those of the gaseous radioactivities very closely. The ratios of CH_3T/CO_2 and $^{85}Kr/CO_2$ are practically flat for both the June-July and the November-February sample analyses.

From a standpoint of documenting all releases of radioactive gases as well as to guard possible fluctuations in concentrations between the points shown in these past graphs, we had installed a system to continuously monitor the activity of the flared gas.[13] This field monitor consisted of two chambers being viewed by scintillation crystals and recording count rates corresponding to the krypton-85 and tritium disintegration energies. These readings, while showing some fluctuations from day to day, do not show any large excursions between the times samples are withdrawn for chemcial and radiochemical analysis. Figure 16 compares the smoothed data from the monitor with the laboratory analyses. The krypton-85 data agree very well; the monitor shows somewhat less tritium content in the gas than the laboratory analysis. However, the count rates in this channel are only about a factor of two above background.

What about the unanswered questions of Gasbuggy? Concerning the concentrations of the radioactive constituents, a natural question to ask is whether this gas is usable for home consumption. The answer must await determination by the proper regulatory agencies; no standards for radioactivities in natural gas exist at this time. It is pretty clear, however, that these concentrations, especially the tritium, need to be reduced. One way to accomplish this might be to rapidly flare one or more of the initial chimney volumes of gas. We have made some calculations which show that this method has considerable promise.[14] More basically, one would like to eliminate tritium from the initial gas itself. About four grams of tritium were left by the Gasbuggy explosive. Perhaps as much as one gram of this was produced by neutron activation of the soil surrounding the explosive, primarily by interaction of neutrons with lithium-6; thus even if one were to use an explosive that did not produce any tritium internally, one would still be left with the contribution of this soil activation. One way this contribution could be eliminated is by shielding interposed between the explosive and the surrounding rock. We have calculated that about one ft of boric acid shielding would be necessary to reduce the amount of tritium produced by lithium activation by a factor of 100. About six inches is necessary to reduce this amount by a factor of ten. Since the use of such shielding might entail expensive underreaming of the emplacement hole, we are studying the possibility of using shielding material inside the explosive canister. Through the use of advanced technology and internal shielding, it is not unreasonable to expect that within the limitations of a 14-inch diameter canister the amount of tritium produced in future underground explosions might be decreased by about a factor of 100 from that of Gasbuggy.

Like all good experiments, Gasbuggy has not only answered some questions but also has raised new ones. It has been realized all along that no single experiment would be able to answer all the questions involved in the use of nuclear explosives for underground engineering applications. Some of these answers will have to come from different detonations at different yields, different depths, at different localities, and in different geologic settings. Even so it is clear that there will be challenging problems to be solved for a very long time to come.

Acknowledgments

I wish to express my deep appreciation to my colleagues at the Lawrence Radiation Laboratory for their help and devoted effort on the Gasbuggy experiment. A lot of the material in this paper has been the result of work by Don Rawson, now with Gulf-General Atomic in San Diego, John Korver, of LRL, as well as Messrs. William Martin and Roy Pritchard of the El Paso Natural Gas Company. I am indebted to them for the use of the figures dealing with the results of the geophysical exploration program. The chemical and radiochemical analysis are the work of Charles Smith of the Lawrence Radiation Laboratory. Some of his material as well as some of the previously mentioned material on chimney configurations was presented at the Society of Petroleum Engineers meeting in Houston in September and October 1968.

REFERENCES

1. G. H. Higgins and T. R. Butkovich, Effect of Water Content, Yield, Medium, and Depth of Burst on Cavity Radii, Lawrence Radiation Laboratory, Livermore, UCRL-50203, February 1967.

2. C. R. Boardman, D. D. Rabb, and R. D. McArthur, Responses of Four Rock Mediums to Contained Nuclear Explosions, J. Geophys. Res. 69, 3457, (1964).

3. C. R. Boardman, G. Meyer, and D. D. Rabb, Macrodeformation Resulting from the Handcar Event, Lawrence Radiation Laboratory, Livermore, UCRL-50149, December 1966.

4. J. T. Cherry, D. B. Larson, and E. G. Rapp, A Unique Description of the Failure of a Brittle Material, Lawrence Radiation Laboratory, Livermore, UCRL-70617, September 1967.

5. E. G. Rapp, Containment of Buried Nuclear Explosions, Lawrence Radiation Laboratory, Livermore, UCRL-50604, in preparation.

6. F. Holzer, Gasbuggy Preshot Summary Report, Lawrence Radiation Laboratory, Livermore, UCRL-50345, November 1967 (PNE-1001).

7. J. T. Cherry, D. B. Larson, and E. G. Rapp, Computer Calculations of the Gasbuggy Event, Lawrence Radiation Laboratory, Livermore, UCRL-50419, May 1968.

8. J. A. Korver and D. E. Rawson, Gasbuggy Postshot Investigation in GB-ER, Lawrence Radiation Laboratory, Livermore, UCRL-50425, April 1968.

9. F. Holzer, Gasbuggy Preliminary Postshot Summary Report, Lawrence Radiation Laboratory, Livermore, UCRL-50386, January 1968 (PNE-1003).

10. D. E. Rawson, J. A. Korver, R. L. Pritchard, and W. Martin, Postshot Geologic Investigations, Project Gasbuggy, Lawrence Radiation Laboratory, Livermore, UCRL-71354, September 1968.

11. D. C. Ward and R. F. Lemon, Status of Reservoir Evaluation Project Gasbuggy, Preprint of paper presented at the Annual Fall Meeting of the Society of Petroleum Engineers, Houston, Texas, September 29, 1968.

12. C. F. Smith and F. F. Momyer, Gas Quality Investigation Program, Status Report for Project Gasbuggy, Lawrence Radiation Laboratory, Livermore, UCRL-71314, September 1968.

13. C. T. Prevo, V. C. Santomassimo, and J. F. Becker, Instrumentation for Monitoring of Kr-85 and H-3 in Natural Gas from the Gasbuggy Chimney, Lawrence Radiation Laboratory, Livermore, Report SDK 68-32, September 1968.

14. G. H. Higgins, D. D. Rabb, and H. C. Rodean, Theoretical and Experimental Studies Relating to the Purging of Radioactivity from a Gas Well Stimulated by a Nuclear Explosion, Lawrence Radiation Laboratory, Livermore, UCRL-50519, December 1968.

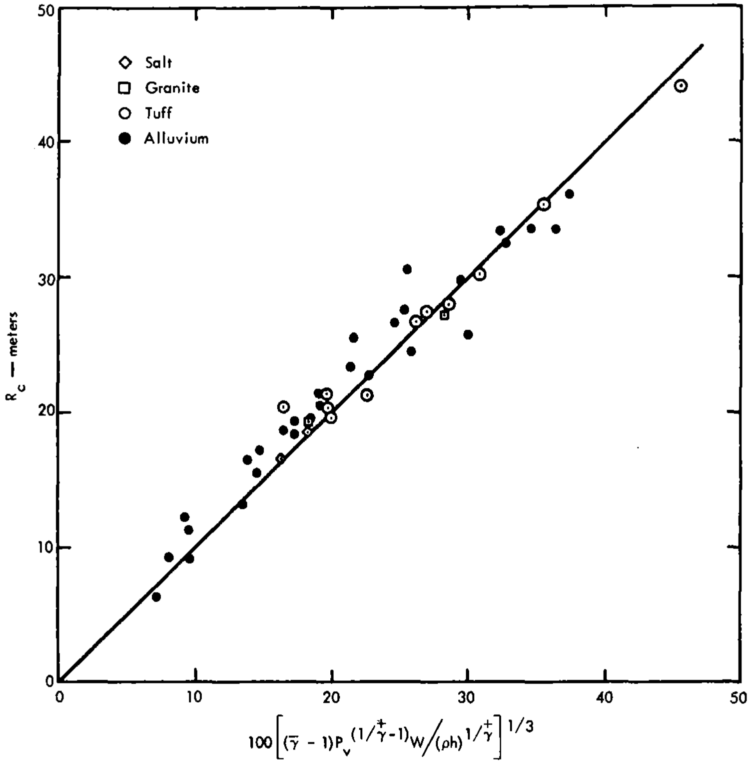

Figure 1. Measured cavity radii as a function of explosive yield, depth of burst, and properties of the medium as derived by Higgins and Butkovich.[1]

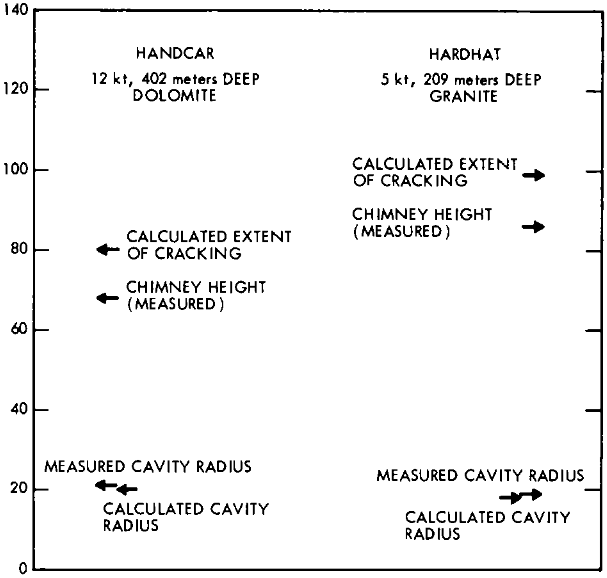

Figure 2. Measured and calculated cavity radii and chimney heights for the Handcar and Hardhat explosions.

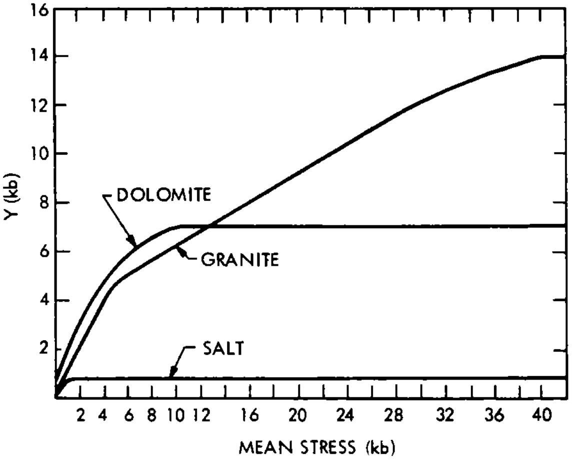

Figure 3. Strength of dolomite and granite as a function of mean stress. Any point above the lines on this graph indicates failure. Hence at low stress levels, corresponding to large distances from the detonation center, dolomite is stronger than granite.

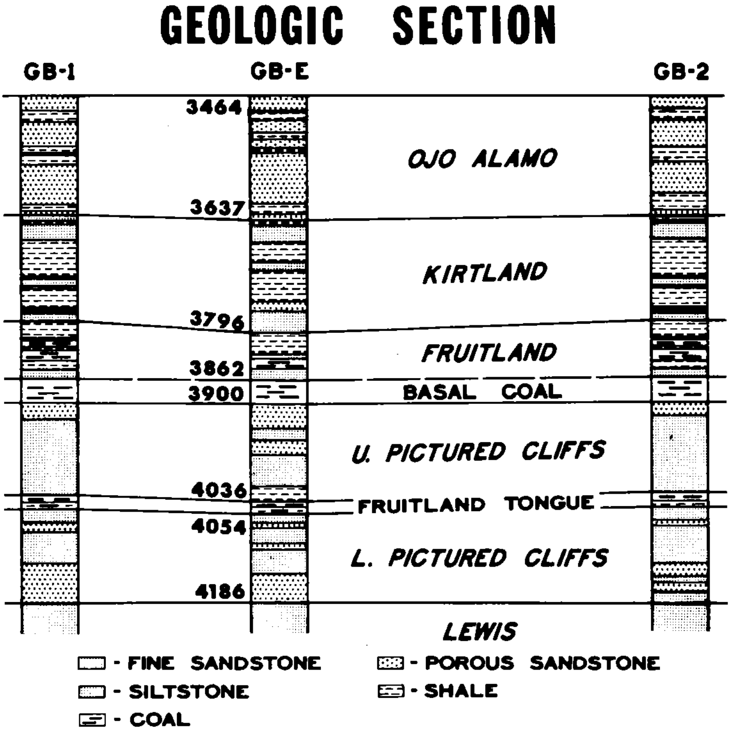

Figure 4. Geologic section at the Gasbuggy site.

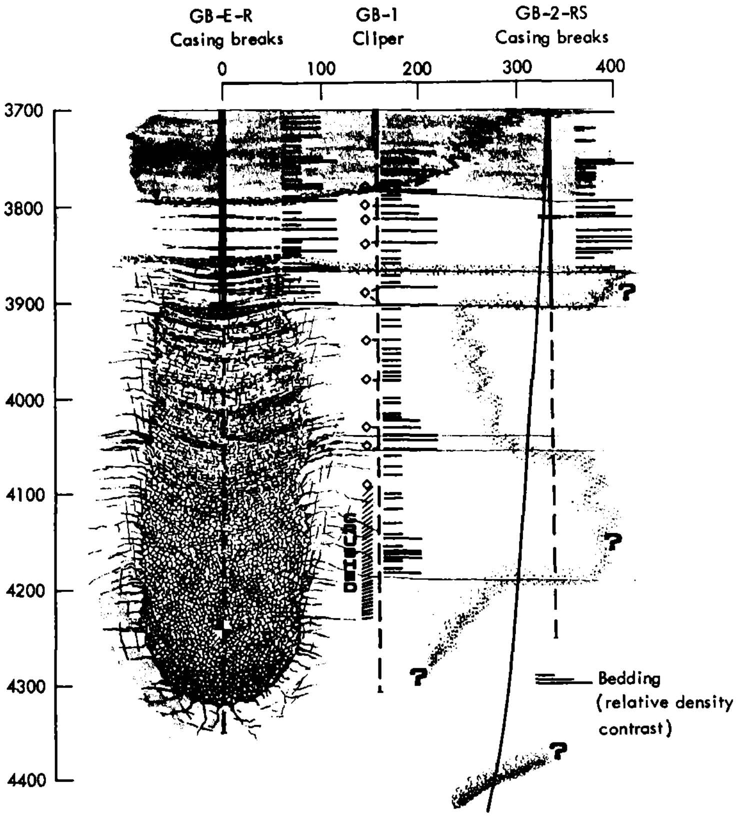

Figure 5. Inferred Gasbuggy chimney, showing casing breaks, bedding planes, and fracture cable data. Preshot holes are shown by dashed lines; postshot holes by solid lines.

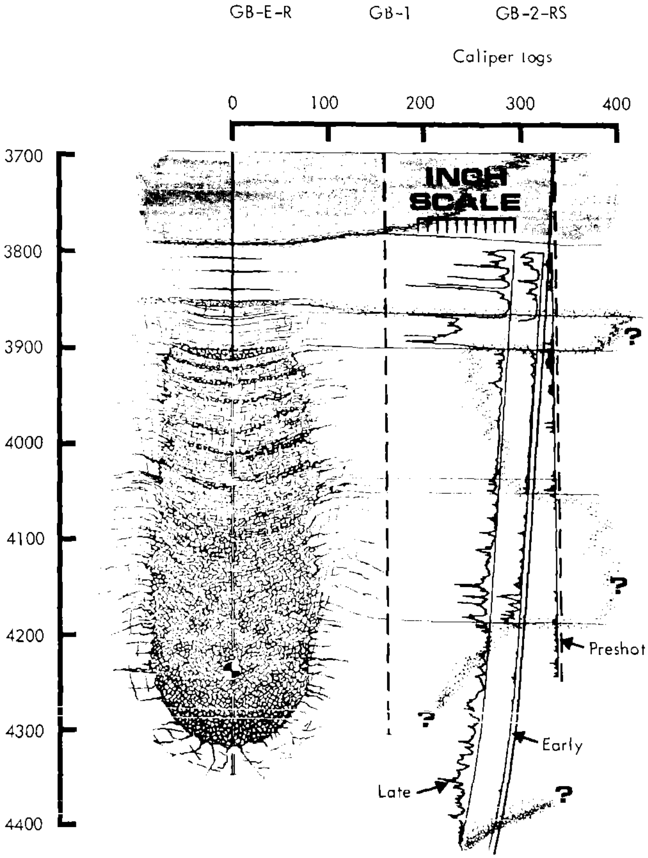

Figure 6. Postshot caliper log data compared with preshot data in GB-2. The two logs in GB-2RS were run 35 hours apart, showing considerable hole deterioration in this interval.

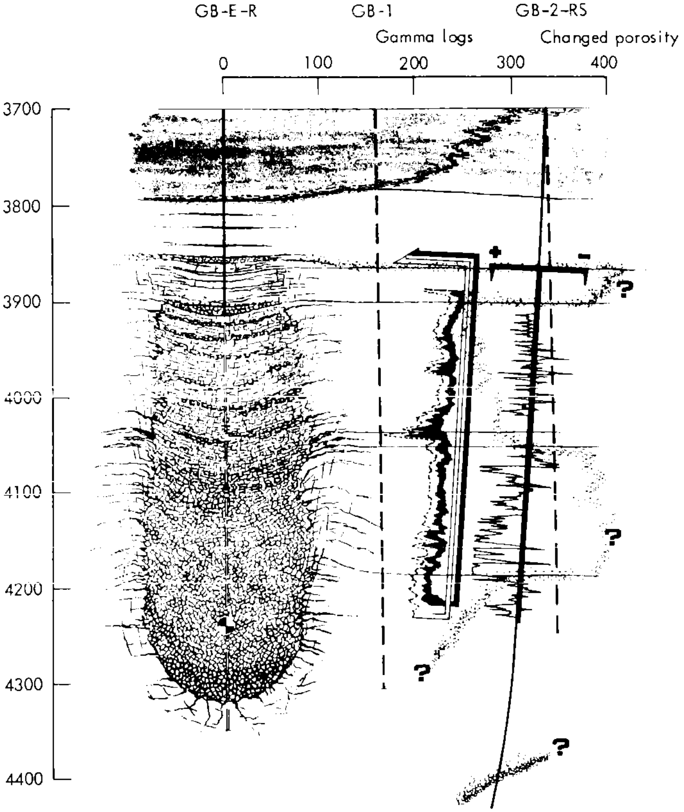

Figure 7. Net change in porosity between GB-2RS and GB-2 data. The gamma logs merely serve to show the degree of formation correlation.

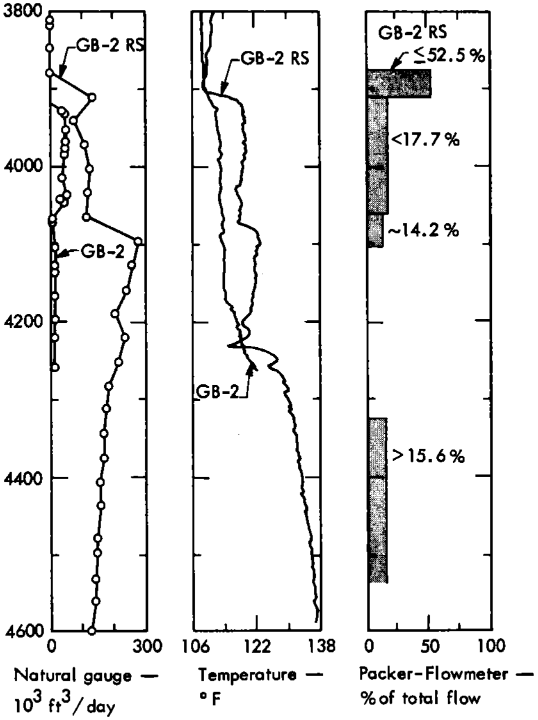

Figure 8. Comparison of pre- and postshot gas production data in holes GB-2 and GB-2RS.

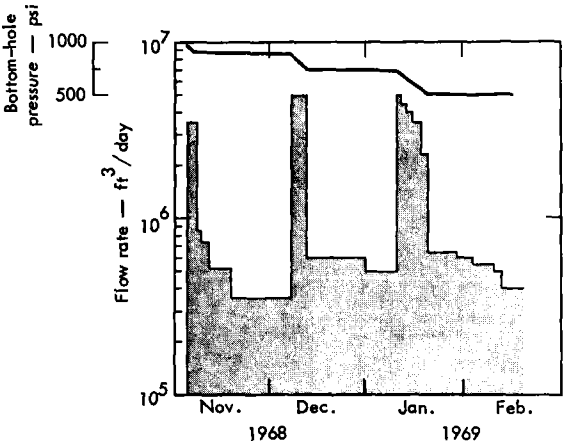

Figure 9. Gas flow rates and bottom hole pressures during the November 1968 - February 1969 flow tests.

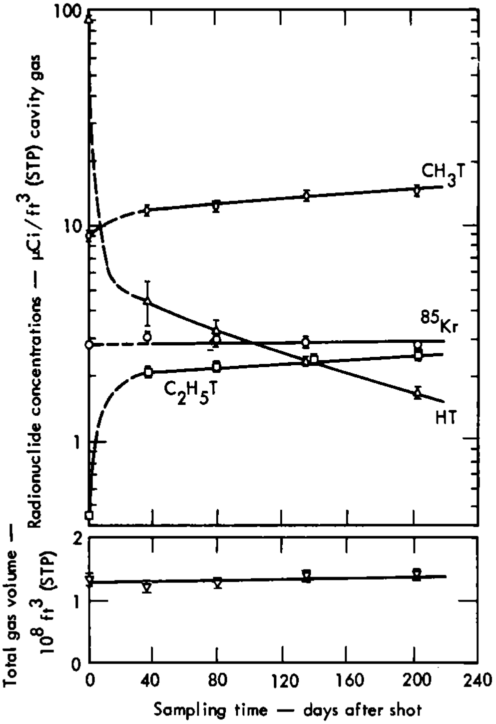

Figure 10. Radionuclide concentrations in the Gasbuggy chimney gas during the seven months following the detonation. Except for a two-day period in January 1968 during which 1.57×10^5 ft^3 of gas were withdrawn, the well was shut in.

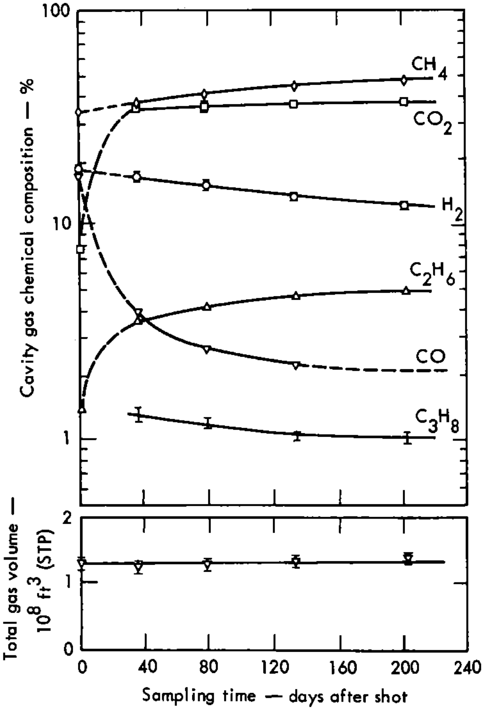

Figure 11. Variations in chemical composition for the seven-month period following the detonation.

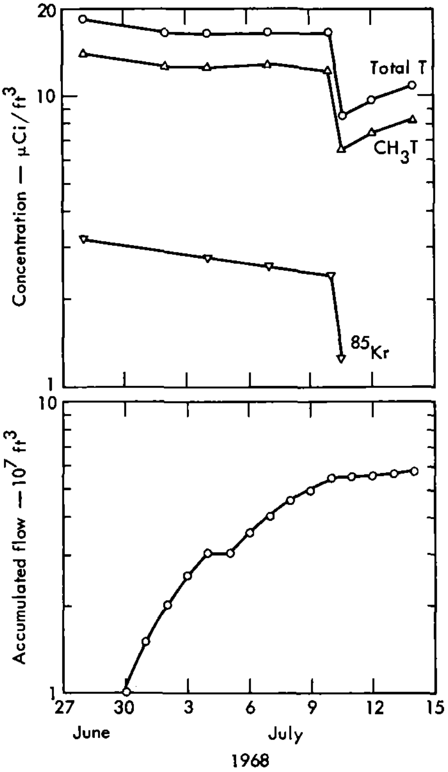

Figure 12. Variations in the tritium and krypton-85 concentrations during the June-July 1968 flow tests when 57 x 10^6 ft^3 of gas were withdrawn.

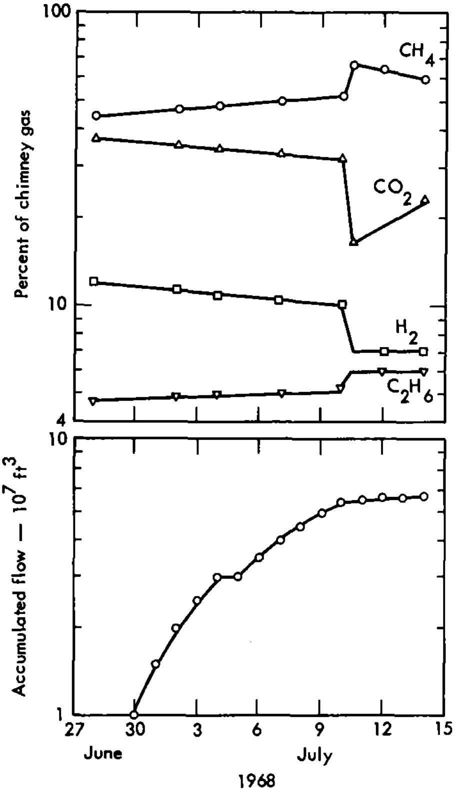

Figure 13. Variations in chemical composition for the June-July 1968 flow tests.

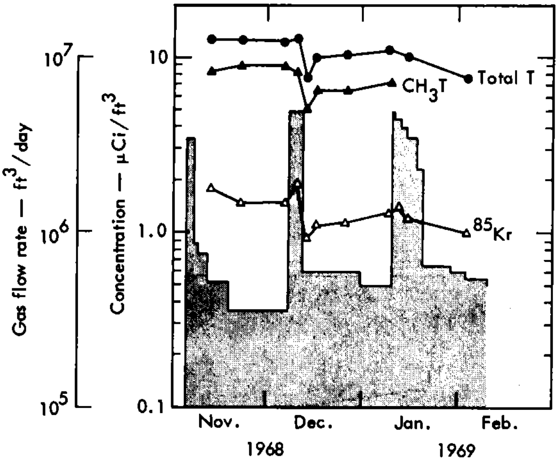

Figure 14. Variations in the tritium and krypton-85 concentrations with flow rates during the November 1968-February 1969 test period.

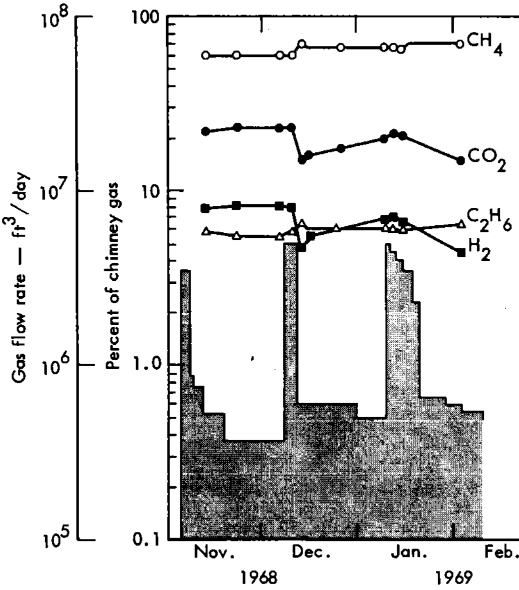

Figure 15. Variation in chemical compositions with flow rates during the November 1968-February 1969 test period.

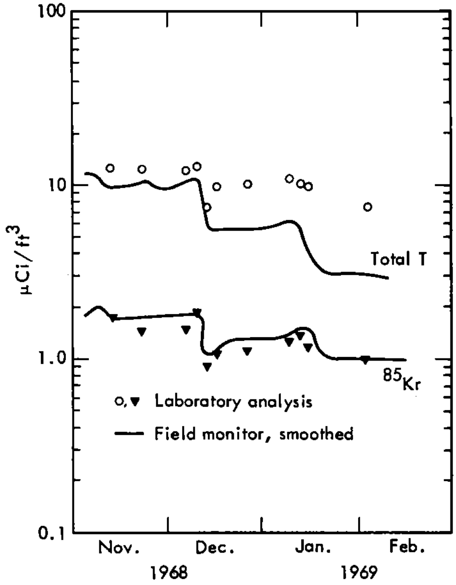

Figure 16. Comparison of data from the field monitor with laboratory sample analysis.

QUESTIONS FOR FRED HOLZER

1. From Don G. Jacobs:

   What measurements are being planned for the Rulison experiment to further elucidate the early changes in downhole chemistry following detonation?

   ANSWER:

   I'm in a very poor position to answer that question and the reason I am is because the Los Alamos Scientific Laboratory is performing the device emplacement and measurements on the Rulison experiment. I must really plead ignorance here. I am not able to answer this question, but I would point out to Dr. Jacobs that Dr. Aamodt of the Los Alamos Scientific Laboratory is attending this meeting and I'm sure that he can answer this question for you.

2. From Alex Gre

   You stated that no cracking was observed to extend near to the level of the Ojo Alamo formation. How was this determined? Are cracks necessarily visible in extracted cores? Are enough holes sampled to warrant a categorical assertion of "no cracking?"

   ANSWER:

   I think taking the last statement first, if I may, no there is no categorical reason to say that there is no cracking to the Ojo Alamo. One of the things that I believe would be very desirable here, to answer this specific question as well as other questions, is another hole--a virgin hole now if you will--drilled from the surface down to depths of perhaps 4500 to 4600 feet. And during this drilling, detailed hydrologic tests of the Alamo could and would be performed to measure pieziometric surfaces, in fact, to duplicate hydrologic tests that were performed in both of the pre-shot holes--GB 1 and GB 2. I think with respect to observance of fractures in cores, I think that if they are observed in cores they are very distinctive--they cannot be mistaken. However, one must realize, and I am sure everyone does, that a hole samples a rather small region of the world down there and it is conceivable that a particular hole may miss a particular fracture. This of course is a rather common experience and this in fact is the reason why two holes were drilled to be shot rather than one. Again, here you are caught in a continual trade-off argument of cost, effort versus information, which of course is not unique to Gasbuggy or Plowshare itself.

3. From Hoyt Whipple:

Were any measurements of carbon-14 activity made on the gas?

ANSWER:

Yes, there were. I'm trying to recall a number and I may have to call on my good friend Dr. Smith to refresh it for me if he can. There is a very, very small amount of carbon-14 in the CO_2, that's what we have analyzed it, 1 pCi per cc roughly of carbon-14. About 1/50th and 1/100th in methane versus CO_2.

TECHNICAL PROBLEMS AND FUTURE UNDERGROUND ENGINEERING EXPERIMENTS*

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ABSTRACT

The technical problems to be solved in future underground engineering experiments are of two kinds. One concerns adequate description of the variation of nuclear explosion effects with physical and chemical properties of the explosion site. The other concerns engineering of the explosive detonation system to provide adequate safety and security, concurrently with minimum total costs per explosion.

The semiempirical equations for explosion effects can be trusted only in the range of explosive energy, depth of burst, and rock type for which there is prior experience. Effects calculations based on the principles of continuum mechanics and measurable geophysical properties appear to work in the few test cases, such as Gasbuggy, to which they have been applied. These calculational methods must be tested in a variety of situations. The relevance of dynamic and static measurements on Dragon Trail, Bronco, Rulison, Sloop, Ketch, and Pinedale to proving the methods are discussed in this paper.

The traditional methods of assembling and fielding nuclear explosives have evolved from practice at the Nevada Test Site. These provide great flexibility and assure maximum recovery of all data from each test, thus minimizing the time required to achieve desired results. Timing and firing, radiation monitoring, explosives assembly and emplacement, explosive performance, weather monitoring, and dynamic measurements of earth and building motion have all been handled traditionally as independent functions. To achieve lower costs in underground engineering experiments and projects, one prototype system combining all electronic, measurement, and communication functions is being built. Much further work will be required to complete this effort, including,

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*Work done under the auspices of the U. S. Atomic Energy Commission.

especially, an examination of safety criteria and means for assuring operational and public safety at reduced costs.

INTRODUCTION

The two preceding papers[1,2] have established the application of nuclear explosions to underground engineering and summarized some of the results obtained from experiments already completed. From these papers it is apparent that the critical technical problem is accurate definition of the mechanical effects required for an application. In addition, the effects related to safety must be understood with sufficient precision to assure minimal risk to the public. Besides the experiments described by Holzer, there have been more than 200 underground nuclear detonations which have yielded information useful in assessing underground engineering. These detonations have occurred in six different rock types and have ranged in yield from one to more than 1,000 kilotons, in depth from a few hundred feet to somewhat over 4,000 feet.

The most utilitarian feature of the underground nuclear explosion as applied to engineering is the combined region of cavity, chimney, and fracture zones. This region contains all the potentially beneficial effects. Figure 1 is a stylized drawing representing the most important features. Briefly, it contains a spherical fractured zone--outside the cavity--whose permeability decreases in the outward direction as the zone grades off into undisturbed rock. The chimney is cylindrical with approximately hemispherical ends. It contains disaggregated, broken rubble which is generally thought to be of high permeability. The lower hemisphere is lined, along its bottom, with a glassy material containing the bulk of the refractory radionuclides; this is the remnant of the initial gas bubble blown in the rock by the explosion. These highly stylized views are subject to a number of limitations which will be discussed later.

Nordyke[1] has discussed the first steps in improving systems for executing underground engineering experiments. These first steps involve integration of the arming, firing, monitoring, data collection, and on-site radiation documentation systems into a single unit. In addition, he has described the projects being considered for execution during the next few years.

As can be seen, there are a number of safety-related issues to be considered along with the beneficial effects. It appears, at present, that product contamination and seismic motion, as it relates to architectural damage, are the two key issues.

In the remainder of this paper, an attempt is made to predict the direction the underground engineering program will take and to anticipate the key technical and safety problems. For simplicity, the discussion is divided into four parts:

- Effects and product contamination.
- Safety-related questions.
- Systems-related questions.
- Future experiments and anticipated results.

EFFECTS OF NUCLEAR EXPLOSIONS

The Explosion-Produced Cavity

The size of the nuclear explosion cavity is related to all of the desirable effects and is a measure of seismic potential. Therefore, cavity size prediction has been the subject of continuing effort since the beginning of the Plowshare program. Analysis of the first underground explosion, Rainier, led to the suggestion of the first empirical relationship between the radius of the cavity produced in rock and the explosive energy. For explosions a few hundred meters deep, the approximation of the cavity radius, $R_C \approx 18\ W^{1/3}$ meters (where W is the number of kilotons of yield), fit most of the explosions in tuff.[3] Later dimensional analysis necessitated inclusion of the effect of overburden pressure,[4] which was tested successfully with field data and led to the equation[5]:

$$R_C = CW^{1/3}/(\rho h)^{1/4} \text{ meters},$$

where C is a constant of proportionality, ρ is density in g/cc and h is depth of burial in meters. In this equation the value of the constant C was found to vary somewhat from one rock type to another, but was usually somewhere in the neighborhood of 70. This equation was found to be valid in five different rock types with the appropriate value of C.

The next attempt at refinement involved analysis of rock properties and the equation of state of the gas produced by vaporization of rock in order to allow prediction of the value of C and the exponent on the ρh term. Higgins and Butkovich[6] used a thermodynamic approach which reduced the scatter on all of the data to $\pm 15\%$ or better for depths up to about 1,000 m. Heard and Ackerman[7] had similar or somewhat better success using the elastic constants of the medium.

From the very beginning, in parallel with the empirical efforts, attempts have been made to explain cavity growth and certain other features from first principles of physics and properties of the rock materials. Nuckolls[4] described the first partially successful calculational attempt. Effort has been continuing in this area. Most recently, the successful prediction of the Gasbuggy chimney height and fracture radius[8] are ample testimony to the success of the method.

When we attempt to extrapolate predictions of the cavity radius into a new material, therefore, we believe the geophysical continuum mechanics calculation gives a reliable estimate. There appear to be no significant differences between cavity size predictions as made with the empirical relationships and with the calculational method at depths of burial up to a few hundred meters or so. But for greater depths of burial the predictions diverge seriously, as shown in Figure 2. For example, at a depth of 5,000 m the cavity radius as predicted by the Boardman *et al.*[5] and Higgins-Butkovich[6] equations is 2.9 times that predicted by Rapp's calculations[9] using the equation of state of Lewis Shale. This discrepancy is extremely serious when one considers that it represents more than a 20-fold disagreement in predicted volume of the cavity and, therefore, probably a similar disagreement in predicted void volume in the chimney.

The importance of testing the validity of these different methods of extrapolation to greater depths--and of obtaining measurements of cavity radii at greater depths--cannot be overemphasized. If a 20-m-radius cavity were desired at a depth of 4,000 m, a yield of 200 kt would be needed on the basis of the calculational prediction, as compared with a yield of only 25 kt on the basis of the empirical equation prediction. Whether one prediction method or the other is valid will make little difference for copper leaching and oil shale retorting, both of which seem to involve shallower depths; however, for both gas stimulation and storage, the difference can be decisive in economic applicability. The key future experiments in this regard are those in which adequate core samples, calculations, and cavity radius measurements are made. Project Rulison and Pinedale or WASP would appear to offer the earliest opportunities for confirmatory measurements of cavity radius for deep shots. However, the status of measurement programs for determination of these features is, as yet, unclear.

Chimney Size

Early experiments at the Nevada Test Site revealed that the cavity formed by explosions was unstable and collapsed. The height to which the collapse extended seemed to be dictated by the bulking ratio of the rock. The cavity volume was found distributed in the voids between rock fragments. Based on the assumption that the interparticulate void was conserved and on empirical observations, Boardman *et al.*[5] suggested that the height of the chimney was related linearly to the cavity radius, which can be represented by the equation $R_c = kh$. Different values of k were derived for several media, ranging from 5 to 7. However, when the Handcar test was conducted in dolomite, the value of k observed was found to be only 3.1, and postshot drilling[10] disclosed a large apical void in the chimney. The mystery caused by the very small chimney remained unsolved until Cherry *et al.*[11] suggested that there was an amazing coincidence between the chimney height and the calculated radius of brittle failure of the rock. Table I shows the computed fracture radius and chimney height for several events, including Gasbuggy, computed from rock properties measured before the event.

It is noteworthy that, in the Salmon shot, the rock (salt) was plastic at every pressure because the confining pressure due to the weight of overlying rocks was above the brittle-ductile failure transition pressure. Therefore, there was no brittle failure and no chimney. Thus, if this model is correct, there is a depth at which the confining pressure will be high enough so that every rock will behave plastically, there will be no brittle failure and, therefore, no chimney. Analysis of Lewis Shale suggests that the depth below which there will be no chimney is between 4,000 and 5,000 m. A chimney and fracture system are believed necessary for recovery of petroleum from oil shale, for copper leaching, and for gas stimulation. The chimney and fracture features would be of little importance for gas storage, since the cavity volume is the useful product, whether or not a chimney is formed. Key tests are possible on each one of the forthcoming proposed underground engineering experiments, provided there is sufficient effort expended to measure the preshot rock mechanics properties and postshot results. To date, effort sufficient only for the Lewis Shale study has been available.

Chimney and Fracture Permeability

The highly idealized chimney shown in Figure 1 suggests very simple relationships for permeability of various regions. Four attempts have been made to determine the permeability in the chimney and fracture areas. During postshot investigations on Rainier, Stead[12] attempted to determine the permeability between tunnels at two different elevations in the lower portion of the Rainier chimney. He was unable, with the test equipment available, to observe any flow of fluid through the chimney material. From this he concluded that the permeability may have been less than about 1 millidarcy. Crude attempts at measurement of the permeability in the fracture region were unsuccessful in distinguishing permeability changes from the preshot range of 1 millidarcy or so.

Boardman and Skrove,[13] working at the Hardhat site, found that there was a regular increase in permeability and microfractures in grains of minerals in the granite as the detonation point was approached, and that the permeability of the chimney region was very high, probably of the order of a million darcys.

Rawson, Boardman, and Jaffe-Chazan[14] observed an increased zone of permeability induced by explosion fractures 46 to 105 m from the 3.1-kt Gnome detonation in bedded salt. No quantitative estimates of the permeability were made. However, a few tens of millidarcys of permeability would explain the observations. In the same experiment, Coffer et al.[15] observed that permeability was increased in some samples of reservoir rocks grouted in holes and exposed to strong shocks during the detonation. In other samples, however, permeability was decreased.

The Gasbuggy experiment allows some direct measurement of permeability increase in the rock and of the permeability of the chimney region itself. At this time, however, the three-dimensional analysis of flow data required for determination of these permeabilities has not been performed. The preshot analysis and one-dimensional methods are incapable of distinguishing this type of variability. A crude qualitative analysis of the data indicates clearly that simple one- or even two-dimensional calculations, assuming constant-permeability regions, are inadequate for interpretation and that the permeability of the chimney and fracture zone is not so high that it can be assumed infinitely large.

Attempts have been made to calculate permeability of chimneys using the void fraction and particle size distribution.[16] For the Hardhat chimney, a value of several megadarcys was inferred in this way, which is consistent with crude measurements. For the Handcar detonation, particle sizes inferred from photographs and an estimate of the void fraction also led to very high permeabilities.

From all of the above, it should be clear that permeability varies greatly from experiment to experiment and from rock type to rock type. Thus, oversimplified models can be grossly misleading. At this time, there is no evidence that a nuclear explosion in any new rock type will produce a region of increased permeability. The permeability must be determined by some predictive model based on measurable rock properties. The work of Boardman and Skrove,[13] coupled with calculational techniques of Cherry et al.,[17] shows promise of providing such a model. There are insufficient data at present to reach conclusions.

It is also obvious that the permeability of the fractured region and chimney are critical in assessing feasibility of gas stimulation, copper leaching, and oil shale retorting. For example, in in situ oil shale retorting the calculated cost of oil recovered can vary by almost a factor of 2, depending on the pressure of air necessary to sustain in situ combustion.[18] This pressure depends directly on the permeability of the fractured chimney and region. In order to provide additional data, direct measurements of permeability in the fractured region produced during Dragon Trail, Rulsion, Pinedale, Bronco, and Sloop are extremely desirable.

Product Contamination

Extensive studies of the Rainier chimney provide the idealized model for radioactivity distribution produced by an underground nuclear explosion.[3] Figure I indicates the key regions. Precisely, there are three regions with which we are now concerned. The first is the lower cavity boundary where the thermally affected rock contains the bulk of refractory radioactivities. This region, composed of some 700 tons of rock per kiloton of yield, is highly contaminated and appears to contain, on the average, more than 90% of the radionuclides whose oxide or hydroxide boiling points are greater than about 1,500° C.

The chimney region, our second region of concern, has distributed throughout it the radionuclides which are gaseous or were gaseous at the time the roof of the initial cavity collapsed. These radioactivities appear to be on the surfaces of the fragments of rock in the chimney and are present in dilute quantity. One detailed study[19] indicates that the major contaminants in this region are cesium, antimony, and ruthenium. In granite, the medium of this test, it would appear that approximately half of the radioisotopes of these three elements are attached to about 125,000 tons of rock per kiloton of yield. There is presently little quantitative information regarding the spatial distribution of the radioactivities, but gamma ray logs of drill holes penetrating the chimney show some gradient of increased contamination from top to bottom. The voids between the fragments contain gaseous radioactivities of krypton, xenon, and isotopes of hydrogen (such as tritium) in the form of water vapor, elemental hydrogen, and hydrocarbons. It has been found that tritium distributes itself ubiquitously with environmental hydrogen so that the water incorporated in the rock both as pore water and water of hydration is contaminated rather uniformly.

In the fractured region, our third region of concern, several studies[3,14,20] have indicated that, at early times, the molten rock can be injected into the fractures as far as one cavity radius beyond the cavity boundary. This has the effect of blocking the fractures and creating zones of contamination beyond the initial cavity.

When the idealized model is applied to a specific site, consideration must be made of the details of chemistry of that site. For example, in gas stimulation, where there is an abundance of elemental carbon and hydrocarbon around the detonation point, the hydrogen isotope distribution is affected. Table II shows the initial radioactivity found in the Gasbuggy chimney,[21] where the ambient methane pressure was about 50 atm prior to detonation. These data indicate that about 25% of the tritium was in the organic phase and 75% in water.

In a different environment--either a different gas reservoir or a completely different environment such as for copper leaching--grossly different distribution should be expected. Predictive models based on thermodynamics have been prepared and evaluated against the Test Site detonations and Gasbuggy.[8] Since the Test Site environment and Gasbuggy provide only two kinds of chemical environment, the range of experience is not adequate to determine the general validity of models. In fact, the preshot predictions of radioactivity distribution for Gasbuggy, based on Test Site information, were different from the observed distribution by several-fold. The importance of obtaining early radioactivity distribution in the gas phase from gas stimulation experiments cannot be overemphasized, therefore.

The key questions besides gaseous distribution involve the solubility of the radioactivities both in the chimney and melt region and the behavior of tritium in the complex chemistry of oil shale retorting. It would appear that the distribution of radioactivity in storage application is less critical because the chimney-cavity region can be flushed and treated prior to insertion of the product to be stored.

SAFETY-RELATED QUESTIONS

Safety-related questions are separated from product contamination questions because they have to do with the local detonation environment at a specific time and place, rather than the broader questions which can result from product contamination. Dynamic venting of radioactivity, ground water contamination, and architectural damage from seismic motion are the three areas included as safety-related questions. Papers to be given later will cover these problems.

SYSTEMS-RELATED DEVELOPMENTS

The first nuclear explosives were detonated either to test the performance of the explosive itself or to determine the effects of the explosion on the ground surface environment. These effects included those of military concern as well as those useful for assessment of civil defense problems which might result from use of nuclear weapons, or from nuclear accidents.

Before 1962, the tests were conducted as "operations" in which a series of experiments was performed in a relatively short time span, usually a few months. In order to accomplish these tests and to obtain both a maximum amount of information and to assure success in each of the experiments, a pseudo-military project-execution program and system was evolved. In this system each project was executed under a technical leader, relatively independent from all other projects. The management and systems problem, therefore, was one of assuring proper interfacing between projects, a minimum of project-to-project interference, and great flexibility from experiment to experiment. This system, for its prupose, has worked very well and continues to be used for weapons development purposes to this time. However, its objectives--speed and flexibility--are not consistent with the requirements for underground engineering applications. The underground engineering experiments and applications require minimum cost and maximum safety. A complete overhaul of the nuclear operations system will be required if industrial applications of nuclear explosives become a reality.

As a first step, an advanced fielding system has been designed, built, and is now undergoing extensive testing. Shown schematically in Figure 3, it combines the nuclear explosive firing and monitoring, experimental data recovery system, meteorological documentation, on-site radiation safety, ground-zero television coverage, and local communications functions. This system replaces, in each named case, a previously completely independent system and eliminates a separate timing system, thus reducing the personnel required to conduct a nuclear explosion. As experience is gained with such a system, one can envision the Control Point being moved farther and farther from the detonation point, until detonation centers established for regions including one or more states could be maintained, carrying out many, many detonations from a single location.

While this system is one step toward greater efficiency, additional simpler concepts must be applied to the off-site safety programs so that a regional, rather than an event-oriented, approach is taken. For example, Projects Rulison, Dragon Trail, and Bronco are separated by at most 60 miles. Yet as presently proposed, each has independent off-site safety programs. By contrast the Nevada Test Site, which occupies a comparable area, is treated as a single region for off-site safety programs. Such a unified approach to the off-site safety program should certainly be applicable to the Rulison/ Dragon Trail/Bronco area as well.

CONCLUSION

In summary, any experiment in underground nuclear engineering must be evaluated in terms of those results which bear on proposed applications from the standpoint of scientific, engineering, and safety requirements. These are cavity radius, R_c; chimney height, H_{ch}; chimney permeability, K_{ch}; product contamination; dynamic venting; ground water contamination; seismic structural damage; and fielding systems development. Table III shows which of these measurements or investigations will be made on upcoming Plowshare experiments, in the author's viewpoint. The experimental plans are not yet fixed, however, and are still flexible and subject to change.

As these experiments are undertaken, there will be opportunity to extend understanding by a significant amount. Obtaining the information will be critical for determining whether or not any one or all of the proposed underground engineering applications of nuclear explosives are technically feasible. Since explosion effects depend so strongly on medium properties, broad generalizations must be carefully avoided and each site and geologic formation must be individually evaluated.

REFERENCES

1. Nordyke, Milo D., Underground Engineering Applications, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-71453 (March 1969) (presented at this Symposium).

2. Holzer, Fred, Summary of Results of Underground Engineering Experience, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-71489 (March 1969) (presented at this Symposium).

3. Johnson, G. W., G. H. Higgins, and C. E. Violet, "Underground Nuclear Explosions," J. Geophys. Res. 64 (10), 1457-1470 (October 1959).

4. Nuckolls, J. H., A Computer Calculation of Rainier, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-5675 (May 1959).

5. Boardman, C. R., D. D. Rabb, and R. McArthur, "Response of Four Rock Mediums to Contained Nuclear Explosions," J. Geophys. Res. 69 (16), 3457-3469 (August 1964).

6. Higgins, G. H., and T. R. Butkovich, Effect of Water Content, Yield, Medium, and Depth of Burst on Cavity Radii, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50203 (Feb. 1967).

7. Heard, H. C., and F. J. Ackerman, Prediction of Cavity Radii from Underground Nuclear Explosions (U), Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50324 (Sept. 1967) (CFRD).

8. Holzer, F., editor, Gasbuggy Preshot Summary Report, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50345 (Nov. 1967).

9. Rapp, E. G., Containment of Buried Nuclear Explosions, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50604 (in preparation).

10. Boardman, C. R., G. L. Meyer, and D. D. Rabb, Macrodeformation Resulting from the Handcar Event, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50149 (Dec. 1966).

11. Cherry, J. T., D. B. Larson, and E. G. Rapp, Computer Calculations of the Gasbuggy Event, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50419 (May 1968).

12. Stead, F., U. S. Geological Survey, Denver, private communication, 1960.

13. Boardman, C. R., and J. Skrove, Changes in the Fracture Permeability of a Granitic Rock Mass Resulting from a Contained Nuclear Explosion, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-14292 (August 1965).

14. Rawson, D., C. Boardman, and N. Jaffe-Chazan, *The Environment Created by a Nuclear Explosion in Salt*, Lawrence Radiation Laboratory, Livermore, PNE-107F (Sept. 1964).

15. Coffer, H. F., B. G. Bray, C. F. Knutson, and D. E. Rawson, "Effects of Nuclear Explosions on Oil Reservoir Stimulation," *J. Petrol. Technol. 16*, 473-480 (May 1964).

16. Lombard, D. B., *The Particle Size Distribution and Bulk Permeability of Oil Shale Rubble*, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-14294 (August 1965).

17. Cherry, J. T., D. B. Larson, and E. G. Rapp, *A Unique Description of the Failure of a Brittle Material*, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-70617 (Sept. 1967).

18. *Project Bronco: A Joint Government-Industry Study of Nuclear Fracturing and In Situ Retorting of Oil Shale*, Proposal to the U. S. Atomic Energy Commission by U. S. Dept. of the Interior, CER-Geonuclear Corp., and Lawrence Radiation Laboratory, Livermore. PNE-1400 (October 1967).

19. Rabb, David D., *Size Distribution Study of Piledriver Particles*, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50489 (Oct. 1968).

20. Johnson, G. W. "Nuclear Explosions--Rainier Test," *Mining Congress J. 44*, 78-80 (1958).

21. Smith, C. F., and F. F. Momyer, *Gas Quality Investigation Program: Status Report for Project Gasbuggy*, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-71314 (Sept. 1968). (Present at Society of Petroleum Engineers Meeting, Houston, Texas, Sept. 29, 1968).

TABLE I. Fracture radius and chimney height.

Event	Medium	Computed fracture radius (m)	Observed chimney height (m)
Handcar	Dolomite	80	68
Hardhat	Granite	97	85
Salmon	Halite	~0	~0
Gasbuggy	Shale-sandstone	120	100

TABLE II. Radioncullides in Gasbuggy cavity gases.

Product	Concentration, μCi/ft^3
^{85}Kr	2.8
HT	91
CH_3T	8.9
C_2H_5T	0.45

TABLE III. Tentative plans for upcoming Plowshare experiments.

	Measurements or investigations to be made:							
Event	R_c	H_{ch}	K_{ch}	Product contam.	Dynamic venting	Ground water	Seis. dam.	Systems devel.
Rulison (Early 1969)	No?	Yes	No	No	Yes	No	Yes	No?
Dragon Trail (Late 1969)	Yes	Yes	Yes	Yes	Yes	No[a]	No[a]	Yes
Bronco (1970?)	Yes	Yes	Yes	Yes	Yes	No[a]	Yes	Yes
Ketch (1970?)	Yes	Yes	Yes	Yes	Yes	No[a]	?	?
Sloop (1970?)	No	Yes	Yes	Yes	Yes?	No[a]	Yes	?
Pinedale-WASP (1972?)	?	?	?	?	Yes	?	Yes	?

[a] *No exposure, so no test data for evaluation.*

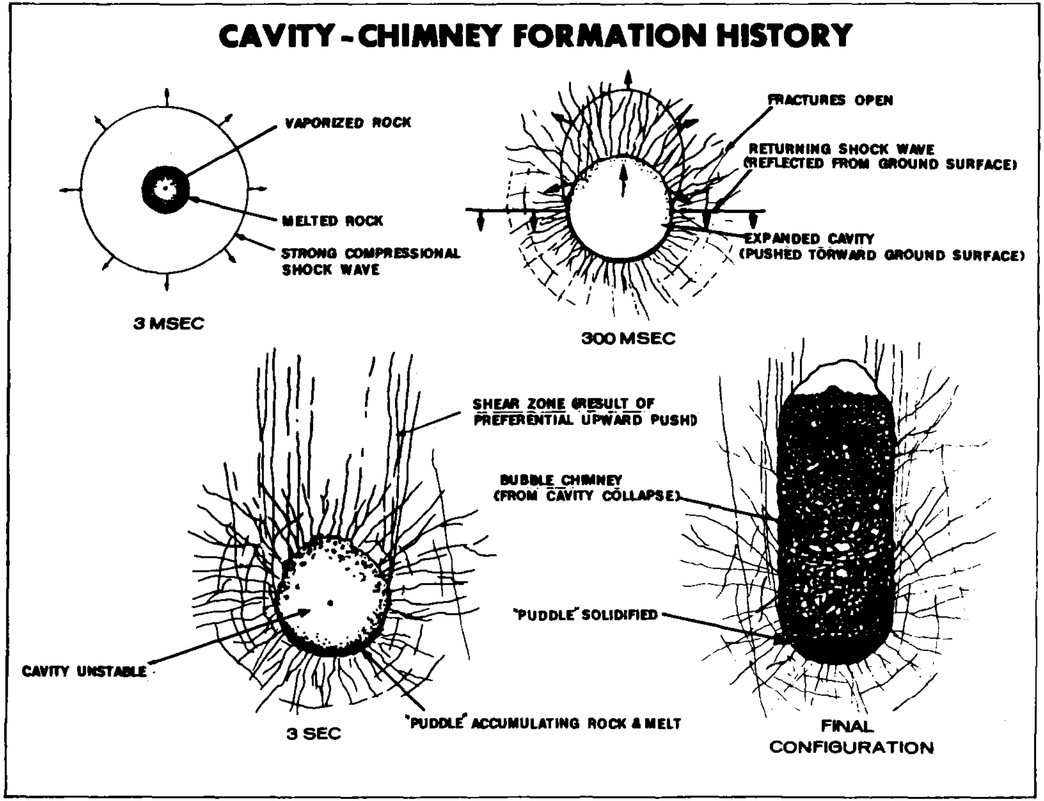

Fig. I Formation history of nuclear explosion cavity and chimney.

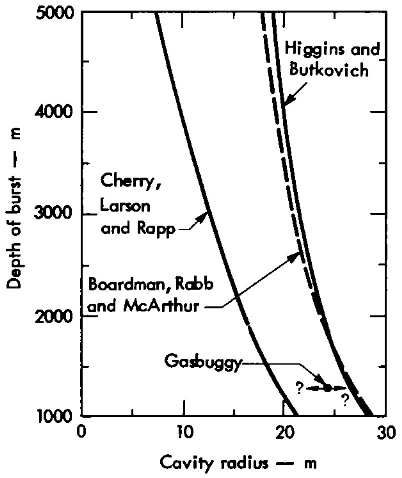

Fig. 2 Predicted cavity radius as a function of depth for a 25-kt shot in Lewis Shale.

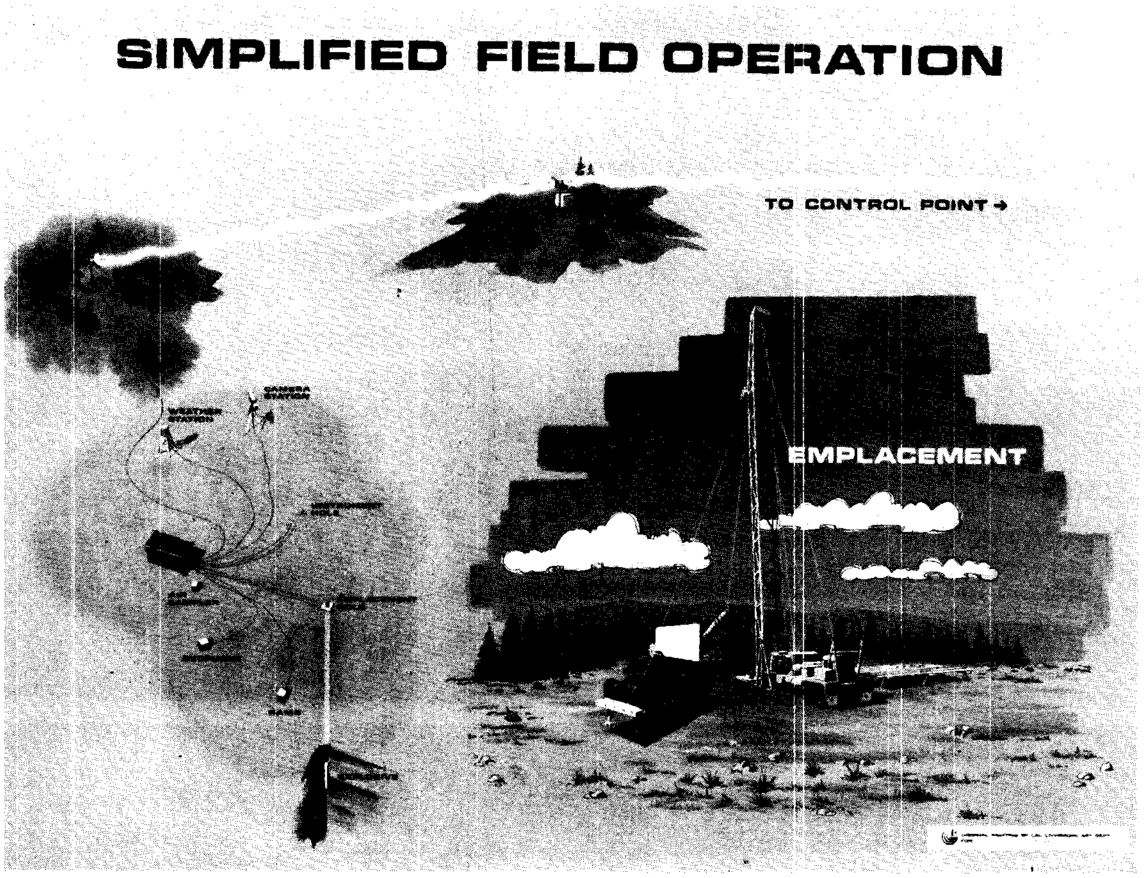

Fig. 3 Schematic concept of a simplified explosion fielding system.

SESSION III - SAFETY ASPECTS
PART A

Chairman: Dr. Roger Batzel
LRL, University of California
Livermore

SAFETY PHILOSOPHY IN PLOWSHARE

Robert H. Thalgott
Nevada Operations Office
U. S. Atomic Energy Commission

ABSTRACT

A nuclear device can be detonated safely when it can be ascertained that the detonation can be accomplished without injury to people, either directly or indirectly, and without unacceptable damage to the ecological system and natural or man made structures.

This philosophy has its origin in the nuclear weapons testing program dating back to the first detonation in 1945 and applies without reservation to Plowshare projects.

This paper therefore will outline the mechanics employed by government in implementing this safety philosophy. The talk will describe those types of actions taken by safety oriented organizations and committees to assure that necessary and desirable safety reviews are conducted.

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The Atomic Energy Commission is responsible for public safety for all U. S. nuclear detonations. Within the Continental United States, the Commission implements this responsibility through its Nevada Operations Office. The AEC's philosophy is to avoid any unnecessary risks, this necessitates evaluation of proposed operations to identify possible problems, taking such measures as are necessary to protect people and minimize damage to property. Although the title of this presentation is "Safety Philosophy for Plowshare" the same policy and safety procedures apply to all of our nuclear operations.

The Nevada Operations Office conducts those studies and reviews which are necessary to reliably predict the effects of nuclear detonations which may affect the safety of people and property. You will hear about some of these studies and prediction activities later in this program. We do not consider ourselves infallible in defining safety problems or at arriving at credible and practical solutions to these problems. For this reason recognized experts in the pertinent scientific disciplines are consulted. These disciplines include but are not limited to: health physics, radiobiology, seismology, hydrology, geology, structural effect from ground motion, and rock mechanics.

This continuing effort on the part of NVOO, its contractors, and consultants, has permitted the programs - involving nuclear detonation both as a part of the weapons program and Plowshare - to go forward essentially without injury to the public or damage to property. I mentioned the efforts of the Nevada Operations Office and its contractors, but would be remiss not to include the efforts of the AEC's Scientific Laboratories and other Governmental Agencies which have contributed so much to our safety program.

Preparation for the safe conduct of an event is based upon prediction of the effects of the maximum credible accident which could befall that event. Necessary steps are taken as indicated by the predictions to ensure that NO limits or guides are exceeded. Precautionary measures are taken to ensure that public safety will be protected, should an accident materialize. NVOO measures and documents the actual effects in order to take emergency action to protect life and property, if necessary, and to accurately identify the effects to improve the accuracy of the predictive effort for future tests.

There are two very important aspects to the predictive and measurement efforts. First, in order to successfully carry on tests, the neighboring population outside the Test Site must be protected from injury. The people must also be adequately informed. Only by dependable predictions can this be done satisfactorily. Good public relations with these people means informing them of possible effects of the event prior to its execution and having that information as accurate as possible.

The second very important function of the measurement effort is to be able to form a firm basis for settlement of valid damage claims and to protect the Government against invalid claims. We must ensure that every effort is made to obtain correct measurements and that these measurements are properly interpreted and made accessible to the public and interested organizations. It is important that the people and interested organizations not only be assured that all steps are taken for protecting the public, but also that they be made aware of the extent and nature of this effort.

Prior to any nuclear detonation there are a series of reviews to ensure that the detonations are conducted safely and within the constraints of the Limited Test Ban Treaty. To achieve the safety in nuclear testing that we desire, a system for review and approval was developed. Slide No. 1 illustrates this system. All nuclear tests do not necessarily involve all of the individual steps depicted; however, unusual tests do receive reviews from the entire system. Slide No. 2 shows a listing of various safety review organizations.

The sponsoring laboratory performs safety evaluations related to nuclear systems safety, that is, procedures associated with assembly of the device, transportation, and emplacement as well as the detonation system. These nuclear safety procedures are later independently reviewed by a group of knowledgeable persons (nuclear safety survey group or nuclear safety study group) and when appropriate, recommendations are made to improve or assure safe assembly, transportation, etc. These study groups are comprised of individuals from different organizations, and as a composite group have a thorough understanding of the nuclear device and associated systems. The stated objective of this review program is to prevent an accidental or unauthorized nuclear detonation.

For contained underground detonations, the sponsoring laboratory independently evaluates and assesses those man-made and natural mechanisms which influence containment of the planned explosion. Each event is then reviewed several times by a Test Evaluation Panel composed of individuals with considerable experience in nuclear testing. The organizations furnishing such individuals are the Los Alamos Scientific Laboratory, Lawrence Radiation Laboratory, Sandia Laboratory, Department of Defense, Air Resources Laboratory-Las Vegas, U. S. Public Health Service, AEC, and independent consultants. Every aspect of the event which might affect containment is reviewed by this Panel several times as preparations for the event are made. A detailed study of the geological features around the shot point is made by the U. S. Geological Survey and presented to the Panel. If there are indications of possible faults or other geologic anomalies which may affect containment, new shot points are recommended by the U. S. Geological Survey. Additional geological information is also obtained by the U. S. Geological Survey from satellite holes drilled to accommodate instrumentation around the emplacement hole. A careful study is made of the drilling, casing, and grouting history of each of the emplacement and satellite holes to ensure that there will be no man-made path to the surface. If there are indications that grouting and casing have left voids, corrective measures are taken and the hole is abandoned.

The proposed stemming plan (that is, the method to be used for filling the emplacement and the instrument holes) is reviewed by the Test Evaluation Panel. If there are doubts as to the capability of the stemming material to contain radioactivity, then appropriate changes are made in the stemming plan. The stemming may range from alternate layers of pea gravel and fine sand to complete cementing of the entire length of the hole, depending upon the shot, media and the location. The same type of review is made to assure containment of a test to be made in a tunnel instead of a drilled hole. Even though these reviews are made and every possible precaution has been taken to ensure that no radioactivity will reach the surface, preparations for detonation of the device assume that the maximum credible release of radioactivity will occur.

AEC Headquarters staff, and finally the Commission, reviews the safety of each event, and if they are satisfied, grant authority for its execution. For detonations where it is anticipated some radioactivity will be released to the atmosphere, such as for cratering experiments, a somewhat similar review is made of the factors which will affect the quantity and nature of the release, including a review of the Laboratory's predictions on the effects of the experiment.

In all cases, regardless of whether the detonation is anticipated to be contained or to vent to the atmosphere, plans are made and steps taken to keep radiation exposures within acceptable levels either by evacuation or asking people to take cover.

The U. S. Public Health Service places off-site radiation monitors in the downwind direction in order that we may get full documentation and take corrective action if there is an accidental release. Mr. John R. McBride of the U. S. Public Health Service will describe this in his paper.

The Test Manager has established an Advisory Panel made up of specialists in meteorology, radiation, and medicine to advise him as to the hazards to be expected from each event. Other disciplines are added to the Panel as conditions warrant. The Panel is chaired by a scientific advisor who is familiar with the nuclear device, timing and firing systems, and program objective.

Although the Test Manager's Advisory Panel may meet several times, months in advance, to discuss specific problems on difficult or unusual shots, the Panel always meets the day before the detonation to hold a readiness briefing in which the control plans are reviewed. A complete weather picture with predictions for shot time meteorological conditions is given and review made of the preparation for on-site and off-site population control. If it is determined that, with the maximum credible accident, the test can be safely carried out, recommendation is made to the Test Manager to proceed with the detonation. The Test Manager's Advisory Panel also reviews the last minute preparation to ensure that the recommendations of the Test Evaluation Panel have been, in fact, carried out in the field.

Complete field preparations are made to document even the smallest release of radioactivity. A system of remote reading monitoring instruments is installed around ground zero and in most cases a remote reading instrument is in the emplacement hole; there is also a ring of air samplers around the ground zero site. We have in the air at shot time at least two airplanes - one equipped with monitoring instruments, the other with sampling equipment. Should there be a release of radioactivity, the monitoring plane makes passes over ground zero and through the radioactive cloud and then keeps track of the leading edge of the cloud. The sampling plane comes in through the cloud and takes samples. These samples are immediately brought back to the Southwestern Radiological Health Laboratory for analysis so that we know exactly what radionuclides are present.

Two additional monitoring planes are also utilized as necessary. These planes are equipped with extremely sensitive detection instruments and with proper equipment aboard to constantly analyze the radioactivity picked up by the detectors. This then provides us with immediate and continuing knowledge of the cloud's contents. The sensitivity of these instruments is such that they can detect changes from natural radon concentrations and are able to discriminate between the debris in the cloud and the natural radioactivity. The tracking effort of these planes is used to position ground monitors in areas which may have been or will be affected.

As you perhaps know, testing has been carried out at the Nevada Test Site for 17 years - underground detonations for about 11 years. We maintain three or more camp sites constantly. The largest of these is Mercury. There are also camps in the forward area, one near the Control Point, and one at Area 12. The population at these camps may vary from 500 to 2,500 people. Although this relatively large number of people live and work within a few miles of the ground zero of even the largest yield tests, there has never been an injury among them as a direct result of a detonation.

We are constantly striving to improve the accuracy of our prediction capabilities in all areas, and have made much progress. We also have come a long way in devising techniques to assure the containment of radioactivity during shot and post-shot related activities. This progress in prediction capability and containment techniques was necessitated by the increased complexity of experiments. In the last analysis all those involved in the test program recognize the potential hazards involved. Therefore, we rely on a proven system based upon taking those actions necessary to protect against the effects of the maximum credible accident.

QUESTIONS FOR ROBERT THALGOTT

1. From Donald E. Barber:

Why is some information concerning Plowshare Programs classified? It is not obvious how national security is at risk.

ANSWER:

So far as I know, the only things that are classified about Plowshare, the Plowshare Program, are these aspects of the device itself which may be classified. The rest of it is completely open.

2. From G. H. Cruelers:

How is a maximum credible accident defined especially when it is known that the stemming was designed to completely contain the products?

ANSWER:

I think this will be touched on in some other talks, but let me briefly go through a series of things that gets us to where we operate. The first is all of our detonations are determined in yield or listed in yield as a design yield and a maximum yield. One of the laboratory people can do this much better than I, but essentially the maximum credible yield is a calculated yield based on the best possible burn efficiencies and so forth. We operate then not from what we expect the device to produce, but this maximum number which gives us one maximum. As far as a release of radioactivity goes, unless we have a great deal of experience in identical geological media and the same location, we go back to a model developed from measurements of an actual venting which was a surprise to us. More or less arbitrarily we've stayed with that. When we are faced with problems which this does not cover, then we dip into somebody's mind and try to envision the worst possible case and develop a model from that. In the case of the upcoming Rulison Project, we will operate both models - one for shot time and one for the possibility of delayed venting. I'm not sure that answered it, but that's about the best I can do.

3. From R. L. Long:

Are the assumed maximum credible accidents as unrealistic as many of those assumed for nuclear reactor analyses?

ANSWER:

I am not familiar with nuclear reactor analyses. I will say again what I stated before. We and the people who preceded us in the testing business have tested for 17 years and the underground testing for 11 years without injury to people and we've done it on the basis that if we are surprised, we will hurt no one. I don't know how you can hang dollars and cents on this. If the Plowshare Industrial Program advances and we have the experience in the field, rather than a single shot in a new location with unknown effects, then we probably can back off from this. But as long as you have a single shot in a single location, new people, new systems, then as long as I'm Test Manager, we will be able to take care of the worst possible accident that anyone can conceive.

4. From R. C. Pendleton:

If all people downwind are informed of hazards, why have the people of Utah not been given this consideration?

ANSWER:

I think I can repeat what you already know, that we do not execute an event either underground or Plowshare if anyone in our system feels that there is an actual safety hazard. When we do have an unexpected venting, or when we have a Plowshare experiment, as soon as we know the content of that cloud, the approximate concentrations of activity in the cloud, and what we expect on the ground, through the Southwestern Radiological Health Laboratory, the State Department of Public Health in Utah is notified where we expect the cloud to go, what we expect to see in the cloud and what we expect on the ground. So through that method at least we thought we were notifying the people in Utah of what happened.

5. From Walt Kozlowski:

You spoke of unnecessary risks, would you please tell us what you would consider necessary risks?

ANSWER:

Any time you deal with explosives or almost any mechanical contrivance there is some risk. There is a risk in walking across the street, there is even a risk in getting out of bed. I consider those risks unnecessary where we are aware of the problem and fail to take care of it. We do not shoot any nuclear detonation under circumstances where we are aware of problems and have no solutions.

6. From J. E. Wallen:

Geological studies are made to study the effects of the detonation on the geology of the area. Why do you not make studies of the total effects of the detonation on the biology of the area? Why do you study only radioactivity effects on man and only radiobiology?

ANSWER:

This question, I guess, is really in two parts, and I am afraid that we have fallen into a trap by not describing more fully our program. Later, I think, in this program there will be a discussion of ecological studies where we are doing total biological studies in several areas where we had no previous experience. Again the same problem with radiobiology when, in fact, we are studying biology or the biological environment and then applying those factors to it which will give us concern because of radionuclides which may be released.

7. From Dr. Tom Rozzell:

Please give more information on the camps at the NTS - what type of people, etc.

ANSWER:

The camps are located at the south edge of the Test Site, the middle point and the northernmost point. They are established mainly for economical reasons - it is cheaper for the people to stay there and work than to bring them back and forth to town. The highest percentage of the population of the Area 12 camp, which is the northernmost camp, is craftsmen. Probably more miners than any other craft because that is the area in which we do mining. This camp population runs usually about 800 people. The Area 6 camp in the center of the Test Site again is mainly occupied by craftsmen and this will pretty well run the gamut since these people work in the so called Yucca Flats area and it is quite convenient to them. The Mercury facility is the largest one. I think we can house around 3,000 people there. This camp is populated by a mixture of crafts, professional people and technicians with, I suspect, a higher percentage of the scientific types than any other type of people. I might point out one fact. All of our water for construction and our potable water comes from water wells on the site. The town of Mercury draws its drinking water from what is known as Well 5 which, aquiferous speaking, is downstream about 1-1/2 miles from a shot, an underground detonation, that was fired there a couple of years ago very close to the water table in that area and in no well have we seen radioactivity. The only place we've found radioactivity in water is when we drill back in the shot points looking for it.

MASS EXTRACTION RATES OF RADIONUCLIDES IN FALLOUT MATERIAL FROM A 170-kt NUCLEAR CRATER*

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Livermore, California 94550

ABSTRACT

The quantity k is defined as the fraction of a nuclide in the environment which must be ingested each day over a given time period to receive a maximum allowable dose, in accordance with the International Commission on Radiological Protection guidelines. Values of k were computed for radionuclides produced in a single cratering detonation using current design technology. A new concept, called the "Mass Extraction Rate," is presented. This concept is defined as the mass of earth material from which the entire quantity of the radionuclide must be extracted and ingested each day by some natural process over a given time interval, which results in a permissible dose. Mass Extraction Rate values are tabulated. A comparison is made between the Mass Extraction Rate and the specific activity methods.

INTRODUCTION

In a report of an LRL study in 1966 (Ref. 1), James and I developed a set of general equations from which individual doses from and the relative significance of radionuclides could be calculated. A table of values resulted, showing (1) k, the fraction of a nuclide that must be ingested each day over any time interval to receive a maximum allowable dose in accordance with International Commission on Radiological Protection (ICRP) guides, and (2) q_0, the disintegration rate of the nuclide at $t = 0$. In our calculations we assumed that neither physical dilution nor biological concentration processes operate, that the radionuclide is always completely biologically available, and that there is no influence by the presence of the stable element. We further assumed that ingestion begins two months after the last detonation (for the case of an isthmian canal) and continues for 50 years. In this paper the same assumptions apply, except that the time intervals over which ingestion is calculated are different. Whereas in our previous study the calculated values of q_0 and k were made for a detonation plan involving fourteen separate detonations over two years and 294 explosives of varying

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*This work was performed under the auspices of the U.S. Atomic Energy Commission

yields, the present set of values involves a single detonation of 170-kt total yield and a quite different explosive design. These differences alter the values of k and therefore the relative significance index. Although separate values of k and of q_0 are classified *and cannot be presented here, the product* kq_0 *in pCi/day is unclassified* and can be computed by anyone who possesses the ICRP Committee II report (Ref. 2).

THE GENERAL EQUATIONS

A certain fraction of each nuclide existing in the environment will be ingested each day. Because of dilution and concentration factors, this fraction will, in general, be a function of time. In Ref. 1, we assumed this fraction per day to be a constant k.

The general equations applicable to the critical organs other than those of the GI tract are:

$$D = \frac{5.1\times10^{-5}\,\epsilon k f_w q_0}{m(\lambda_e - \lambda_r)}\left[\frac{e^{-\lambda_r t_1} - e^{-\lambda_r t_2}}{\lambda_r} - \frac{e^{-\lambda_e t_1} - e^{-\lambda_e t_2}}{\lambda_e}\right] \text{ for } \lambda_e \neq \lambda_r \qquad (1)$$

and

$$D = \frac{5.1\times10^{-5}\,\epsilon k f_w q_0}{m\lambda^2}\left[e^{-\lambda t_1}(\lambda t_1 + 1) - e^{-\lambda t_2}(\lambda t_2 + 1)\right] \text{ for } \lambda_e = \lambda_r = \lambda \qquad (1a)$$

where

D = dose (rem),
ϵ = effective energy (MeV) = ΣEF (RBE)n (Table 5 or 5A of Ref. 2),
k = fraction of a nuclide existing in the environment ingested per day,
f_w = fraction of the amount of nuclide ingested, which reaches the critical organ,
q_0 = disintegration rate of nuclide at $t = 0$(pCi),
m = mass of organ (g),
λ_e = effective decay constant in the critical organ (day^{-1}),
λ_r = radioactive decay constant (day^{-1}).

In Equations (1) and (1a) and in the equations which follow, $t = 0$ when ingestion begins; t_1 to t_2 is the time interval over which the dose to the critical organ is calculated; $q = q_0$ when $t = 0$. (When the critical organ is not part of the GI tract, it is assumed that there is no significant time interval between ingestion of the nuclide and entrance into the critical organ.)

The general equation that applies to the critical organs that are part of the GI tract is

$$D(\text{rem}) = \frac{5.1\times10^{-5}\,\epsilon\tau k q_0 e^{-\lambda_r t_3}}{2m\lambda_r}\left(e^{-\lambda_r t_1} - e^{-\lambda_r t_2}\right), \tag{2}$$

where

τ(days) = *the time interval the material remains in the critical* organ of the tract as given in Table 11 of Ref. 2,
t_3(days) = the time between ingestion and entrance into the critical organ of the tract; viz., $t_3 = 0$ for stomach, 1/24 for small intestine, 5/24 for upper large intestine, and 13/24 for lower large intestine.

In using Equations (1), and (1a), and (2), t_1 will be taken as zero, i.e., the time of ingestion. The fact that radioactive decay takes place between ingestion and arrival of the nuclide at the critical organ of the tract (except for the stomach) is accounted for by the first exponential.

Applying the appropriate values from Tables 8 and 11 of Ref. 2, the equations then become:

Stomach (S)

$$D(\text{rem}) = 4.4\times10^{-9}\,\frac{\epsilon k q_0}{\lambda_r}\left(1 - e^{-\lambda_r t_2}\right). \tag{3}$$

Small Intestine (SI)

$$D(\text{rem}) = 3.8\times10^{-9}\,\frac{\epsilon k q_0}{\lambda_r}\,e^{-0.042\lambda_r}\left(1 - e^{-\lambda_r t_2}\right). \tag{4}$$

Upper Large Intestine (ULI)

$$D(\text{rem}) = 6.3\times10^{-8}\,\frac{\epsilon k q_0}{\lambda_r}\,e^{-0.21\lambda_r}\left(1 - e^{-\lambda_r t_2}\right). \tag{5}$$

Lower Large Intestine (LLI)

$$D(\text{rem}) = 1.27\times10^{-7}\,\frac{\epsilon k q_0}{\lambda_r}\,e^{-0.54\lambda_r}\left(1 - e^{-\lambda_r t_2}\right). \tag{6}$$

No significant error is introduced by ignoring the first exponential in Equations (4), (5), and (6), provided the radioactive half-life, T_r, is long enough. The following table shows such errors:

T_r	SI	ULI	LLI
	The calculated value of D will be too large by a factor of:		
1/4 day	1.12	1.8	4.5
1/2 day	1.06	1.3	2.1
1 day	1.03	1.16	1.5
2 days	1.01	1.08	1.2
4 days	1.01	1.03	1.10

If the allowable dose to the critical organ in a time period t_1 to t_2 is substituted for D in Equations (3) through (6), it is possible to calculate the fraction, k, of q_0 which must be ingested per day each day from $t = 0$ to t_2 for the delivered dose to equal the allowable dose. The lower the value of k, the less may be ingested, and therefore the more hazardous the nuclide. Used in this way, then, k has a physical meaning. Also, by comparing one k value with another, the most important nuclide, under a given set of assumptions, can be determined at a glance.

The value of k changes with the dose criterion and time period used for the allowable dose. For example, if a nuclide has a half-life of one week, then 0.0033 rem delivered in the first week is more restrictive (gives a lower value of k) than if the criterion of 0.17 rem delivered in the first year is used. For example, where the critical organ is the LLI, k can be several orders of magnitude lower if the period zero to one week is used rather than zero to one year. On the other hand, for a nuclide with a long half-life, which is accumulated slowly (like strontium-90), a short time period gives a less restrictive k value.

Because of these effects, any list of k values must clearly indicate both the dose criteria and the time period, t_1 to t_2.

The physical and biological parameters used in the calculations are given in Appendix A. The annual permissible dose values used to calculate k are:

Organ	D (rem/year)
Total body, gonads	0.17
Skin, bone	3
All others	1.5

With the aquatic system in mind, it is assumed here that ingestion begins one week after detonation. It is difficult to imagine ingestion by a sizable portion of the population beginning sooner, except via the milk pathway.

In cases where a parent nuclide decays to a shorter-lived daughter, the contribution to the dose by the daughter is included. Where the daughter is longer lived, each nuclide is calculated separately.

For a given nuclide, where there is more than one critical organ shown in bold face type in Ref. 2, each case was calculated. In every instance, the first case listed proved to be the most hazardous and is the only one included here.

MASS EXTRACTION RATES

If we know the total mass of earth material (fallback, ejecta, and fallout) with which a radionuclide is mixed, we can compute the Mass Extraction Rate, MER. MER is defined as the mass of earth material from which the entire quantity of the radionuclide in that mass must be extracted and ingested each day, by some natural process, over a given time interval, resulting in a permissible dose. This is done simply by multiplying the fraction per day, k, by the total mass of earth material, M, and is known as the Mass Extraction Rate:

$$\text{MER (g/day)} = k\ (\text{day}^{-1})\ M(\text{g}).$$

The total mass of earth material is computed by first determining the fraction of the total radioactivity produced per gram of fallout or fallback in the most highly concentrated samples, then taking the reciprocal. In such samples, refractory and volatile particulates do not differ in their fraction-per-gram values by more than ±50%. Using the most highly concentrated samples gives the lowest value of M and, therefore, the lowest values of MER.

Assuming the crater dimensions scale as yield raised to the 1/(3.4) power (Ref. 3), the mass of earth material with which the radioactivity is mixed scales as the yield raised to the 3/3.4 power, or 0.88. Then the fraction per gram for a 170-kt crater is

$$\frac{100}{170}^{0.88} = 0.63$$

times that for a 100-kt crater. That is, the total mass of earth material with which the nuclides from a 170-kt crater is mixed is 1.6 times that from a 100-kt crater.

Tritium is a special case because it is not particulate. In cratering events, virtually all tritium appears as HTO, and is more uniformly mixed with the total mass of earth moved than are particulates. Figure 1 illustrates that the mass concentration of tritium in fallback is essentially constant from the bottom of the apparent crater down to the working point 315 feet below. Figure 2 (taken in part from Ref. 4) shows the decrease in tritium concentration with distance from surface zero. The highest concentrations are found in fallback.

Using appropriate M values for particulates and tritium, MER values were computed for all nuclides. (See Tables I through III.) Nuclides having MER values greater than 2000 g/day have been excluded. Also, values of MER were computed for three different time intervals. Table I lists values of MER where t_2 equals the time required to obtain 99% of the dose at the permissible annual dose rates. Table II lists values of MER where t_2 equals one year, and Table III lists MER values where t_2 equals 30 years.

Interpretation of MER Values

Using 12.4 day thallium-202 as an example, Table I indicates that if an individual, by some natural process, managed to extract and ingest each day 100% of the thallium-202 contained in 14 grams of the most concentrated fallout, he would receive 0.334 rem to the LLI, and he would receive that dose in the first 82 days after beginning ingestion. Further, 0.334 rem is 99% of the dose he could ever receive from thallium-202 regardless of how much longer he ingests at that MER. Also, 0.334 rem in 82 days is the permissible annual dose rate of 1.5 rem/year (not necessarily the permissible dose rate in 82 days). Table II indicates that at a MER of 60 g/day, he would receive 1.5 rem to the LLI during the first year. However, he would again receive 1.485 rem (99%) in the first 82 days, or at an annual rate of 6.6 rem/year for the 82 days, and about 0.015 rem in the remaining 283 days. At a MER of 60 g/day he would receive 0.48 rem in the first week after ingestion begins. Table III shows that at a MER of 1800 g/day he would receive 1.5 rem/year x 30 years = 45 rem in 30 years. However, he would receive 44.5 rem in the first 82 days.

On the other hand, using 27.8-year strontium-90 as an example, Table I shows that at a MER of 1100 g/day, the individual would receive three rem to the bone during the first year. (Table II did not include strontium-90 because 128 years are required to receive 99% of the dose at a constant MER.) Table III indicates that a MER of only 180 g/day are required to receive three rem/year x 30 = 90 rem to the bone over 30 years. At a MER of 180 g/day, a dose of only 0.5 rem to the bone is received during the first year. The reason is that strontium-90 has a long, effective half-life in the bone; viz., 17½ years.

The Terrestrial Environment

What is a reasonable maximum value of a MER in the terrestrial environment? The U.S. Public Health Service reports data on institutional total diets of children (9-12 years of age) during April-June 1968 (Ref. 5). Samples of the edible portion of the diet for a full week (21 meals plus soft drinks, candy bars, or other in-between snacks--drinking water excluded) were collected and analyzed. Twenty-one states are represented, covering all sections of the nation, including Alaska and Hawaii. Potassium intake was measured, with a low value of 0.8 g/day in Louisville, Kentucky, in June, and high value of 4.2 g/day in St. Louis, Missouri, in May. The institutional average for all locations and months was 2.7 g/day.* Since typical soils contain about 2½ W/% potassium, the intake of the biologically available potassium must have resulted from actual extraction rate of about 100 grams of soil per day. Virtually all of this potassium must have come terrestrially, because the sea contains a low concentration of potassium (380 ppm), and sea animals do not concentrate potassium in their muscle by more than about an order of magnitude. So, for the terrestrial environment, an actual extraction rate of 100 g/day would appear to be a reasonable overall value for elements completely and rapidly available from fallout to man's food via the soil-root pathway. MER values larger than 100 g/day would result in doses proportionately smaller than permissible doses.

Harley (Ref. 6) reports that the natural uranium in the terrestrial diets of San Francisco residents in 1966 was 413 μg/year. Uranium is ubiquitous in nature and is found to be present at about 3 ppm. Then the actual extraction rate for uranium is 0.38 g/day, compared to 100 g/day for potassium. So for most elements, the actual extraction rates will be appreciably lower than 100 g/day.

Using one week after the detonation for initial ingestion is much too conservative for the soil-root pathway. With the exceptions of tritium, tungsten-181 and tungsten-185, the MER values of each nuclide in Tables I through III increase to 100 g/day or greater if 51 days after detonation is taken as the start of ingestion. This is caused simply by radioactive decay. The time from detonation to onset of ingestion required to raise MER values to 100 g/day is shown in Table IV for each nuclide.

The Aquatic Environment

Most elements are concentrated, some by large factors, by aquatic food chains. The ratio of the mass of element per mass of edible portions of aquatic food to the mass of element per mass of water ranges from less than one (e.g., Cl, Ref. 7) to as much as 10^5 (e.g., Cd). Therefore, the aquatic pathway is potentially more hazardous than the soil-root pathway. Concentration factors are important when the specific activity method is

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* Incidentally, this potassium intake results in a potassium-40 intake of 2200 pCi/day, and an annual dose of 0.060 rem to a child's total body, or about one-third of the ICRP permissible dose.

used to estimate hazards from radioactivity in aquatic foods. The specific activity principle was first developed by a Working Group of the Committee on Oceanography of the NAS-NRC (Ref. 8). In their report, this principle is stated: "...if the specific activities (that is, the radioactive proportions of the elements) of the chemical elements in the sea in the environment of human food organisms are maintained below the allowable specific activities for those elements in the human body or human food, no person can obtain more than an allowable amount of radioactivity from the sea, regardless of his habits." In the Maximum Extraction Rate concept, specific activities are not used, and as stated before, it is assumed that there is no influence by the stable element. In fact, the specific activity could be infinite (i.e., no stable element or carrier element present). It is still essential that extraction and ingestion of a radionuclide from a certain quantity of fallout occur each day to receive the maximum dose, independent of specific activity. This is no criticism of the specific activity method. The two concepts complement each other. It might be possible to show that, for nuclides with low MER values, the specific activity is in fact lower than the maximum permissible specific activity. Conversly, where the MPSA is exceeded, MER values might be inordinately high.

Also, concentration factors do not apply in the MER concept. For example, the MER for mercury-203 is 58 g/day giving 1.5 rem to the kidney during the first year. Let's assume that oysters concentrate mercury by a factor of 10^5, and that six oysters are eaten each day during the year. For a kidney dose of 1.5 rem, each group of six oysters must extract the mercury-203 from 58 grams of fallout per day, not 58×10^{-5} g/day. The MER value remains fixed regardless of the concentration factor.

Tritium

Let us assume Leipunsky's often quoted value for tritium production of 6.7×10^3 per kt of fusion. The MPC_w for the general population is 10^{-3} µCi/cc. Therefore, 1.1×10^{16} cc of water (a body of water 80 feet deep and 7.6 miles in radius) is required to dilute all of the tritium to MPC_w. It is assumed that all the tritium produced is immediately present and available in the aquatic system and that this body of water is never mixed with other water.

However, tritium decays with a 12.26-year half-life, so that to receive $0.17 \times 30 = 5.1$ rem in 30 years would require a body of water 80 feet deep with a 4.1-mile radius, and it is assumed that man is in equilibrium with this body of water only.

In a harbor or canal application, for example, a small fraction of the total tritium would appear in the ocean, harbor, or canal water shortly after a detonation; therefore, smaller volumes of water would be required for dilution. Furthermore, turbulent mixing in the ocean, tidal changes in the harbor, and currents in the canal would further reduce the tritium concentrations.

Radiotungstens

Tungsten-181 and tungsten-185 appear to be potentially the most troublesome particulates, according to MER analysis. Preliminary data (Ref. 9) indicate about 1% of the tungsten isotopes in Cabriolet fallout is leached by sea water when continuously shaken for three weeks. If only 1% is available, the MER values for tungsten must be multiplied by 100 to compute the actual extraction rates required to receive a permissible dose. Furthermore, changes can be made in the design of the 170-kt explosive under consideration to greatly reduce the quantities of the radiotungstens produced.

OTHER METHODS

Tamplin (Ref. 10) and Ng (Ref. 11) have made estimates of doses to man which could be received through forage-cow-milk, soil-root, and aquatic pathways. They use the specific activity concept, and where uncertainties exist, employ values of parameters which tend to maximize the estimates. Also, their assumptions lead to maximum doses. For example, they assume instantaneous equilibrium in the biological exchangeable pool. Ingestion begins immediately at shot time. Tamplin (Ref. 10), in dealing with the aquatic system, calculates 30-year doses to the infant bone for external activation products and fission products from a cratering explosive of 1-Mt total yield and 10-kt fission yield. The infant remains an infant for the 30-year period. The greatest dose from activation products is 430 rad from phosphorus-32, assuming all the phosphorus-32 is in the aquatic system. Using the same q_0 of phosphorus-32 used by Tamplin (4.2×10^{16} pCi), an actual extraction rate 2.2×10^4 g/day is required for a dose of 430 rad. His greatest dose from fission products is 2540 rad from antimony-126. Again using his q_0 of antimony-126 (9.6×10^{16} pCi), an actual extraction rate of 4.6×10^6 g/day is required. The present MER analysis indicates that many nuclides are potentially more troublesome than either phosphorus-32 or antimony-126, the two nuclides appearing as most important in Ref. 10. Further, it seems extremely improbable that an actual extraction rate in excess of one ton per infant per day could ever be accomplished by any natural process. This comparison illustrates that ultraconservative assumptions, regardless of the method employed, can result in misleading conclusions.

It is interesting to compare mass concentrations of the lead-210 produced by the explosive and the lead-210 naturally present. In equilibrium with uranium-238 is its 21-year daughter lead-210. At 3-ppm uranium, the mass concentrations of lead-210 is one Ci per 10^{12} grams of soil. The explosive produces a lead-210 mass concentration of one pCi/gram. Therefore the mass concentration of lead-210 from the explosive about equals that already naturally present.

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REFERENCES

1. R. A. James and E. H. Fleming, Jr., Relative Significance Index of Radionuclides for Canal Studies, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50050-1 (Sept. 13, 1966).

2. Recommendations of the International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2 (Pergammon Press, London, 1959).

3. M. D. Nordyke, The Sedan Event, AEC Rept. PNE-242F, August 6, 1965.

4. J. J. Koranda, J. R. Martin, and R. W. Wikkerink, Leaching of Radionuclides at Sedan Crater, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-70630 (March 25, 1968).

5. Radiological Health Data and Reports, Vol. 10, No. 1, January 1969.

6. John Harley, Radionuclides in Food. Paper given at the Symposium on the Biological Implications of the Nuclear Age, Lawrence Radiation Laboratory, Livermore, March 5-7, 1969.

7. W. H. Chapman, H. L. Fisher, and M. W. Pratt, Concentration Factors of Chemical Elements in Edible Aquatic Organisms, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50564 (Dec. 30, 1968).

8. Disposal of Low-Level Radioactive Waste into Pacific Coastal Waters, NAS-NRC Publication 985 (1962).

9. F. L. Harrison, to be published.

10. A. R. Tamplin, H. L. Fisher, and W. H. Chapman, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50163, Part V. "Estimation of the Maximum Dose from Internal Emitters in the Aquatic Food Supply" (Sept. 10, 1968).

11. Y. C. Ng, and S. E. Thompson, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50163, Part II. "Estimation of the Maximum Dose from Internal Emitters" (Dec. 14, 1966).

Table I

Ingestion begins 1 week after detonation

(t_2 is the time required to obtain 99% of the dose at the permissible annual dose rate)

Fission products						Induced activities					
Nuclide	T_r*	Critical organ	No. of days	Dose (rem)	MER (g/day)	Nuclide	T_r	Critical organ	No. of days	Dose (rem)	MER (g/day)
I^{131}	8.05d	Thyroid	74	0.303	2.2	W^{185}	74 d	LLI	490	2.00	0.55
Te^{132}	78 h	LLI	21	0.088	21	W^{187}	24 h	LLI	6.6	0.027	2.0
Ba^{140}	12.8 d	LLI	84	0.346	25	Pb^{203}	52 h	LLI	14	0.058	4.7
Pr^{143}	13.7 d	LLI	90	0.370	85	W^{181}	140 d	LLI	920	3.78	5.0
I^{133}	21 h	Thyroid	8.3	0.033	100	Tl^{202}	12.4 d	LLI	82	0.334	14
Mo^{99}	66.5 h	Kidney	21	0.087	150	Rb^{86}	18.66d	T. B.	123	0.057	47
Ce^{143}	33 h	LLI	9.1	0.037	190	Hg^{203}	46.6 d	Kidney	310	1.28	50
Nd^{147}	11.1 d	LLI	73	0.300	240	P^{32}	14.3 d	Bone	135	1.12	110
Pm^{149}	53 h	LLI	15	0.060	250	Hf^{181}	43 d	LLI	280	1.16	190
Sr^{89}	52.7 d	Bone	500	4.08	270	Ta^{182}	115 d	LLI	760	3.10	320
Ru^{103}	40 d	LLI	260	1.08	280	Tl^{201}	73 h	LLI	20	0.082	370
Rh^{105}	36 h	LLI	9.9	0.040	280	Ca^{45}	165 d	Bone	1570	12.9	600
Zr^{95}	65.5 d	LLI	430	1.77	300	Mn^{54}	312 d	LLI	2100	8.43	600
Ce^{141}	32.5 d	LLI	210	0.880	380	Np^{239}	2.35d	LLI	16	0.064	770
Ru^{106}	1.0 y	LLI	2400	9.85	430	Co^{58}	71 d	LLI	470	1.92	1100
Te^{131m}	1.2 d	LLI	7.9	0.032	730	S^{35}	88 d	Testis	790	0.370	1200
Y^{91}	58.8 d	LLI	390	1.59	750	Cs^{134}	2.1 y	T. B.	5100	3.40	1500
Ag^{111}	7.5 d	LLI	50	0.202	820	Fe^{59}	45 d	LLI	297	1.21	1600
Sn^{125}	9.4 d	LLI	62	0.254	1400						

*d = day, h = hour, y = year.

Table II

Ingestion begins 1 week after detonation

(t_2 = 1 year)

Fission products				Induced activities			
Nuclide	T_r*	Critical organ	MER (g/day)	Nuclide	T_r	Critical organ	MER (g/day)
I^{131}	8.05d	Thyroid	10	W^{185}	74 d	LLI	0.42
Ba^{140}	12.8 d	LLI	110	W^{181}	140 d	LLI	2.4
Ru^{106}	1.0 y	LLI	130	Tritium	12.26y	Body tissue	18
Ce^{144}	284 d	LLI	140	Hg^{203}	46.6 d	Kidney	58
Sr^{89}	52.7 d	Bone	190	Tl^{202}	12.4 d	LLI	60
Zr^{95}	65.5 d	LLI	270	W^{187}	24 h	LLI	110
Ru^{103}	40 d	LLI	370	Rb^{86}	18.66d	T. B.	140
Te^{132}	78 h	LLI	420	Ta^{182}	115 d	LLI	170
Ce^{141}	32.5 d	LLI	650	Ca^{45}	165 d	Bone	180
Y^{91}	58.8 d	LLI	700	Mn^{54}	312 d	LLI	190
Sr^{90}	27.8 y	Bone	1100	Hf^{181}	43 d	LLI	240
Nd^{147}	11.1 d	LLI	1200	P^{32}	14.3 d	Bone	300
Cs^{137}	30 y	T. B.	1200	Cs^{134}	2.1 y	T. B.	500
				S^{35}	88 d	Testis	625
				Pb^{203}	52 h	LLI	820
				Co^{58}	71 d	LLI	900
				Pb^{210}	21 y	Kidney	1200

* day = day, y = year, h = hour.

Table III

Ingestion begins 1 week after detonation

(t_2 = 30 years)

Fission products				Induced activities			
Nuclide	T_r*	Critical organ	MER (g/day)	Nuclide	T_r	Critical organ	MER (g/day)
Sr^{90}	27.8 y	Bone	180	W_{185}	74 d	LLI	12
I^{131}	8.05d	Thyroid	320	Tritium	12.26y	Body tissue	35
Cs^{137}	30 y	T. B.	1300	W^{181}	130 d	LLI	60
Ru^{106}	1.0 y	LLI	2000	Pb^{210}	21 y	Kidney	450
				Hg^{203}	46.6 d	Kidney	1700
				Tl^{202}	12.4 d	LLI	1800

*y = year, d=day

Table IV

Time from detonation to onset of ingestion required to increase MER values to 100 g/day

(tritium excluded)

t_2 = 99% D		t_2 = 1 year		t_2 = 30 years	
Nuclide	t (day)	Nuclide	t (day)	Nuclide	t (day)
I^{133}	8	Tl^{202}	16	W^{181}	110
Pr^{143}	10	I^{131}	34	W^{185}	233
W^{187}	13	Hg^{203}	43		
Te^{132}	14	W^{185}	588		
Pb^{203}	17	W^{181}	759		
Rb^{86}	27				
Ba^{140}	33				
Tl^{202}	42				
I^{131}	51				
W^{185}	562				
W^{181}	612				

APPENDIX A

INDUCED AND RESIDUAL ACTIVITIES

Nuclide	Critical organ	T_r^*	λ_r (day^{-1})	T_e (day)	λ_e (day^{-1})	ϵ (MeV)	*m* (g)	f_w
Tritium	Body tissue	12.26 y	1.55 (-4)[†]	1.2 (1)	5.77 (-2)	1.0 (-2)	4.3 (4)	1
Be^{7}	LLI	53 d	1.31 (-2)			8.5 (-3)		
C^{14}	Fat	5730 y	3.31 (-7)	1.2 (1)	5.77 (-2)	5.4 (-2)	1.0 (4)	5 (-1)
Na^{22}	T. B.	2.60 y	7.3 (-4)	1.1 (1)	6.30 (-2)	1.6	7.0 (4)	1
Na^{24}	SI	15.0 h	1.11			2.7		
Si^{31}	S	2.62 h	6.35			5.9 (-1)		
P^{32}	Bone	14.3 d	4.85 (-2)	1.41 (1)	4.91 (-2)	3.5	7.0 (3)	3.75 (-1)
S^{35}	Testis	88 d	7.87 (-3)	7.72 (1)	8.97 (-3)	5.6 (-2)	4.0 (1)	1.3 (-3)
Cl^{36}	T. B.	3.1 × 10^{5} y	6.14 (-9)	2.9 (1)	2.39 (-2)	2.6 (-1)	7.0 (4)	1
K^{42}	S	12.4 h	1.34			1.5		
Ca^{45}	Bone	165 d	4.20 (-3)	1.63 (2)	4.25 (-3)	4.3 (-1)	7.0 (3)	5.4 (-1)
Ca^{47}	Bone	4.53 d	1.53 (-1)	4.53	1.53 (-1)	2.6	7.0 (3)	5.4 (-1)
Sc^{46}	LLI	83.8 d	8.3 (-3)			4.0 (-1)		
Cr^{51}	LLI	27.8 d	2.49 (-2)			1.0 (-2)		
Mn^{54}	LLI	312 d	2.22 (-3)			1.3 (-1)		
Mn^{56}	LLI	2.58 h	6.45			1.1		
Fe^{55}	Spleen	2.4 y	7.9 (-4)	3.88 (2)	1.79 (-3)	6.5 (-3)	1.5 (2)	2 (-3)
Fe^{59}	LLI	45 d	1.54 (-2)			2.9 (-1)		
Co^{58}	LLI	71 d	9.8 (-3)			1.7 (-1)		
Co^{58m}	LLI	9 h	1.85			1.9 (-2)		
Co^{60m+g}	LLI	5.24 y	3.64 (-4)			4.4 (-1)		
Cu^{64}	LLI	12.9 h	1.29			1.6 (-1)		
Zn^{65}	T. B.	243 d	2.85 (-3)	1.94 (2)	3.57 (-3)	3.2 (-1)	7.0 (4)	1 (-1)
Rb^{86}	T. B.	18.66 d	3.71 (-2)	1.32 (1)	5.25 (-2)	7.0 (-1)	7.0 (4)	1
In^{114m+g}	LLI	50 d	1.38 (-2)			9.3 (-1)		
Sb^{124}	LLI	60.2 d	1.15 (-2)			6.8 (-1)		
Cs^{134}	T. B.	2.1 y	9.05 (-4)	6.5 (1)	1.065 (-2)	1.1	7.0 (4)	1
Eu^{152}	LLI	13 y	1.46 (-4)			6.5 (-1)		
Eu^{154}	LLI	16 y	1.28 (-4)			6.9 (-1)		
Dy^{159}		144 d						
Hf^{181}	LLI	43 d	1.61 (-2)			2.2 (-1)		
Ta^{179}		600 d						
Ta^{182}	LLI	115 d	6.02 (-3)			3.8 (-1)		
Ta^{183}		5.0 d						
W^{178}		22 d						
W^{181}	LLI	140 d	4.95 (-3)			4.7 (-2)		
W^{185}	LLI	74 d	9.30 (-3)			1.4 (-1)		
W^{187}	LLI	24 h	6.93 (-1)			3.6 (-1)		

APPENDIX A (Continued)

Nuclide	Critical organ	T_r^*	λ_r (day^{-1})	T_e (day)	λ_e (day^{-1})	ε (MeV)	m (g)	f_w
W^{188}		69 d						
Ir^{192}	LLI	74 d	9.30 (-3)			4.2 (-1)		
Hg^{203}	Kidney	46.6 d	1.49 (-2)	1.1 (1)	6.3 (-2)	1.5 (-1)	3.0 (2)	2.6 (-1)
Tl^{201}	LLI	73 h	2.28 (-1)			1.0 (-1)		
Tl^{202}	LLI	12.4 d	5.60 (-2)			2.3 (-1)		
Tl^{204}	LLI	3.75 y	5.05 (-4)			2.5 (-1)		
Pb^{203}	LLI	52 h	3.20 (-1)			5.1 (-2)		
Pb^{210}	Kidney	21 y	8.64 (-5)	4.94 (2)	1.40 (-3)	1.0 (1)	3.0 (2)	1.0 (-2)
Bi^{207}	LLI	30 y	6.23 (-5)			2.4 (-1)		
Bi^{210}	LLI	5.0 d	1.39 (-1)			9.5 (-1)		
U^{233}	LLI	1.62×10^5 y	1.17 (-8)			4.9 (-1)		
U^{234}	LLI	2.48×10^5 y	7.65 (-9)			4.8 (-1)		
U^{235}	LLI	7.13×10^8 y	2.66 (-12)			5.2 (-1)		
U^{236}	LLI	2.39×10^7 y	7.95 (-11)			4.5 (-1)		
U^{237}		6.75 d						
U^{238}	LLI	4.51×10^9 y	4.21 (-13)			4.3 (-1)		
Np^{237}	Bone	2.14×10^6 y	8.90 (-10)	7.3 (4)	9.5 (-6)	4.9 (-1)	7.0 (3)	5.4 (-5)
Np^{239}	LLI	2.35 d	2.95 (-1)			1.4 (-1)		
Pu^{238}	Bone	89 y	2.13 (-5)	2.3 (4)	3.01 (-5)	2.8 (2)	7.0 (3)	2.4 (-5)
Pu^{239}	Bone	24,360 y	7.80 (-8)	7.2 (4)	9.63 (-6)	2.7 (2)	7.0 (3)	2.4 (-5)
Pu^{240}	Bone	6,760 y	2.81 (-7)	7.1 (4)	9.77 (-6)	2.7 (2)	7.0 (3)	2.4 (-5)
Pu^{241}	Bone	13 y	1.46 (-4)	4.5 (3)	1.54 (-4)	1.4 (1)	7.0 (3)	2.4 (-5)
Am^{241}	Bone	458 y	4.15 (-6)	5.1 (4)	1.36 (-5)	2.8 (2)	7.0 (3)	2.5 (-5)
FISSION PRODUCTS								
Br^{82}	T. B.	35.3 h	4.71 (-1)	1.3	5.33 (-1)	1.8	7.0 (4)	1
Sr^{89}	Bone	52.7 d	1.31 (-2)	5.25 (1)	1.32 (-2)	2.8	7.0 (3)	2.1 (-1)
Sr^{90}	Bone	27.8 y	6.85 (-5)	6.4 (3)	1.08 (-4)	5.5	7.0 (3)	9.0 (-2)
Y^{91}	LLI	58.8 d	1.08 (-2)			5.9 (-1)		
Zr^{95}	LLI	65.5 d	1.06 (-2)			2.4 (-1)		
Mo^{99}	Kidney	67 h	2.49 (-1)	1.5	4.61 (-1)	4.5 (-1)	3.0 (2)	6.0 (-2)
Ru^{103}	LLI	40 d	1.73 (-2)			1.93 (-1)		
Ru^{106}	LLI	1.0 y	1.90 (-3)			1.3		
Rh^{105}	LLI	36 h	4.61 (-1)			1.9 (-1)		
Ag^{111}	LLI	7.5 d	9.25 (-2)			3.7 (-1)		
Cd^{115m}	LLI	43 d	1.61 (-2)			6.1 (-1)		
Sn^{121m}		76 y						
Sn^{123m}		125 d						
Sn^{125}	LLI	9.4 d	7.37 (-2)			9.3 (-1)		

APPENDIX A (Continued)

Nuclide	Critical organ	T_r^*	λ_r (day^{-1})	T_e (day)	λ_e (day^{-1})	ϵ (MeV)	m (g)	Γ_w
Sb^{124}	LLI	60 d	1.16 (-2)			6.8 (-1)		
Sb^{125}	LLI	2.7 y	7.04 (-4)			1.8 (-1)		
Sb^{126}		12.5 d						
Sb^{127}		3.7 d						
Te^{127m}	Kidney	105 d	6.6 (-3)	2.3 (1)	3.01 (-2)	3.2 (-1)	3.0 (2)	2.0 (-2)
Te^{129m}	LLI	34 d	2.04 (-2)			9.3 (-2)		
Te^{131m}	LLI	1.2 d	5.77 (-1)			5.5 (-1)		
Te^{132}	LLI	78 h	2.13 (-1)			8.6 (-1)		
I^{131}	Thyroid	8.05 d	8.61 (-2)	7.6	9.12 (-2)	2.3 (-1)	2.0 (1)	3.0 (-1)
I^{133}	Thyroid	21 h	7.96 (-1)	8.7 (-1)	7.92 (-1)	5.4 (-1)	2.0 (1)	3.0 (-1)
Cs^{136}	T. B.	13 d	5.33 (-2)	1.1 (1)	6.30 (-2)	6.5 (-1)	7.0 (4)	1
Cs^{137}	T. B.	30 y	6.32 (-5)	7.0 (1)	9.9 (-3)	5.9 (-1)	7.0 (4)	1
Ba^{140}	LLI	12.8 d	5.41 (-2)			1.12		
Ce^{141}	LLI	32.5 d	2.13 (-2)			1.7 (-1)		
Ce^{143}	LLI	33 h	5.04 (-1)			4.9 (-1)		
Ce^{144}	LLI	284 d	2.44 (-3)			1.3		
Pr^{143}	LLI	13.7 d	5.06 (-2)			3.2 (-1)		
Nd^{147}	LLI	11.1 d	6.25 (-2)			2.6 (-1)		
Pm^{147}	LLI	2.6 y	7.3 (-4)			6.9 (-2)		
Pm^{149}	LLI	53 h	3.13 (-1)			4.1 (-1)		
Sm^{153}	LLI	47 h	3.53 (-1)			2.4 (-1)		
Eu^{155}	LLI	1.8 y	1.054 (-3)			7.5 (-2)		

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*d = day, h = hour, y = year.

†Numbers in parentheses are exponents of 10.

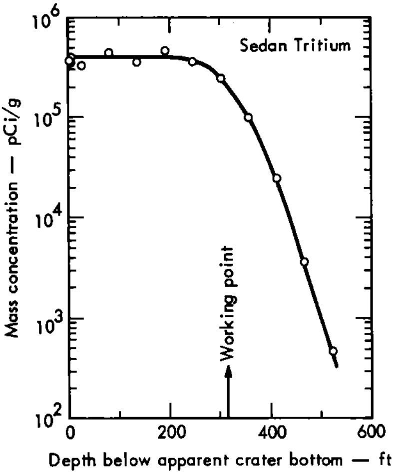

Figure 1. Mass concentration of tritium vs. depth in Sedan fallback.

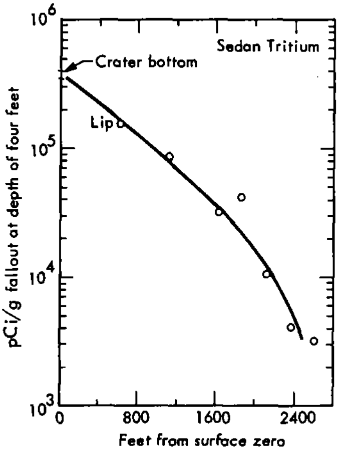

Figure 2. Mass concentration of tritium vs. distance in Sedan.

QUESTIONS FOR EDWARD FLEMING

From Alex Grendon:

Since your method seems to have indicated an annual dose of 16 millirem from potassium-40, which I believe is much higher than the value computed by more direct means, have you analyzed the cause of the difference and does it suggest a source of error in your model?

ANSWER:

It does seem high and I admit that. A value for adults is closer to 30 millirems, but these are children and as a result I multiplied by two taking into account the fact that their body weight is about a factor of two less than an adult's.

From C. L. Pringle:

Are plant metabolism studies continuing to determine nuclide concentrations in the food plants - beans, corn, grass, etc. - grown in soil? Are such results published?

ANSWER:

I'm not very familiar with such work. I believe people from our Biomedical Division at LRL could answer that question better than I; and Dr. Shore, the Division Leader of the Biomed Division, will speak here, I believe it's Thursday; and I'm sure he will be happy to answer that question for you.

From C. L. Pringle:

Will your computations as presented be published in the Proceedings?

ANSWER:

Yes

From E. A. Martell:

Comment on the specific and total activity of cesium-137, strontium-89, and strontium-90 in the cloud from a cratering shot at optimum depth 30 minutes after detonation. What are the consequences of depositing the total cloud debris over approximately 1,000 square miles?

ANSWER:

I don't have the numbers at hand, Ed. I have them at the laboratory.

Moderator: I think the question is to answer the question as to the total activity of each of these species. Are you prepared to speak to that?

ANSWER:

If that's the essence of the question, I cannot and the reason is that the number of curies of each nuclide produced in the excavation explosives is classified Secret/Restricted Data. And that was what I was referring to. I hope that that information will shortly be unclassified or declassified by the AEC. Now the concentration of the cloud, on the other hand, is not classified although I don't happen to have the numbers handy. I'll be glad to write you a letter.

5. From John Martin:

How were the worst-case fallout samples selected?

ANSWER:

The calculations were scaled from Sedan. We took many, many samples from Sedan and analyzed them both by wet chemistry and by spectroscopy and I simply picked the most concentrated sample that was obtainable out of those many, many samples. And the concentrations differed per nuclide and, as I mentioned in the paper, the concentrations were about an order of magnitude higher for particulates than for tritium.

6. From John Martin:

What criteria were used for the tritium values?

ANSWER:

I assume you mean ICRP dose criteria. Tritium - using body tissue as the critical organ and 0.17 rems per year to that tissue.

RADIOACTIVITY SOURCE TERMS FOR UNDERGROUND ENGINEERING APPLICATION*

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ABSTRACT

The constraints on nuclide production are usually very similar in any underground engineering application of nuclear explosives. However, in some applications the end product could be contaminated unless the proper nuclear device is used.

This fact can be illustrated from two underground engineering experiments--Gasbuggy and Sloop. In the Gasbuggy experiment, appreciable tritium has been shown to be present in the gas currently being produced. However, in future gas stimulation applications (as distinct from experiments), a minimum production of tritium by the explosive is desirable since product contamination by this nuclide may place severe limitations on the use of the tritiated gas. In Sloop, where production of copper is the goal of the experiment, product contamination would not be caused by tritium but could result from other nuclides: Thus, gas stimulation could require the use of fission explosives while the lower cost per kiloton of thermonuclear explosives could make them attractive for ore-crushing applications.

Because of this consideration, radionuclide production calculations must be made for both fission and for thermonuclear explosives in the underground environment. Such activation calculations on materials of construction are performed in a manner similar to that described in another paper, but radionuclide production in the environment must be computed using both

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

fission neutron and 14-MeV neutron sources in order to treat the "source term" problem realistically.

In making such computations, parameter studies including the effects of environmental temperature, neutron shielding, and rock types have been carried out. Results indicate the importance of carefully evaluating the radionuclide production for each individual underground engineering application.

INTRODUCTION

It is necessary to ascertain the total "source term" (radionuclide production) resulting from the detonation of an underground engineering explosive to allow adequate analysis to be formulated of both the safety and economic aspects of an application. In the realm of safety, although the radioactivity produced is not immediately broadcast to the biosphere, possible accidental seepage to the surface must be considered, as must potential contamination of mobile ground water.

The economic aspects of the application are directly affected in those cases where the product undergoes a refining process of some sort prior to its ultimate utilization; if the raw material contains appreciable quantities of radioactivity, the processing equipment must be designed to prevent unacceptable radiation exposures to the equipment operators.

Finally, the question which impacts on both the safety and economic areas is that of acceptable product contamination: What is the initial concentration of radioactivity and what is the cost of reducing the initial levels of radioactivity to those required by accepted safety standards?

RADIONUCLIDE PRODUCTION

Sources of Radionuclides

Fission Products.--Although the yields of the various fission products may differ appreciably for different fissile materials and are sensitive to the energy of the neutrons initiating the fission, existing studies[1-3] enable adequate estimates to be made of fission product production in Plowshare explosives.

Neutron Activation Products: Device Components.--As presently defined, "device components" include those portions of a Plowshare explosive package which can be subjected to very high time-integrated neutron fluxes. Radionuclide production in these components can be extensive; for sake of completeness, multiple neutron-induced reactions producing radioisotopes far from the stability curve[4] are included in the calculation.

Materials farther away from burning fissile or thermonuclear fuel are exposed to somewhat lower time-integrated neutron fluxes; hence, first-order reactions predominate in the production of radionuclides.

Neutron Activation Products: Canister and Soil.--Activation products formed at relatively large distances from neutron sources will consist primarily of those made by the neutron capture process. Whether neutron shielding material will be employed (as is the case for nuclear excavation explosives) or not, the neutron spectrum incident upon the canister and soil will include some high-energy neutrons, and some (n, 2n), (n, p) and (n, α) reactions will be induced in the canister and adjacent soil. However, the neutron spectrum "softens" rapidly in the shielding and soil or rock (especially where significant water is present), thus causing the overall predominance of (n, γ) reactions.

CALCULATIONS (CODES AND PROCEDURES)

Computation of Neutron Fluxes

High-flux Regions.--Neutronic calculations may be made of the explosion phase of a fission or thermonuclear device using neutron diffusion or Monte Carlo computational techniques. Current versions of computer programs using these techniques not only provide for the calculation of neutron fluxes (divided into a number of energy groups) as a function of time in any region of the device included in the problem, but also allow the calculation of nuclide production from multiple reactions occurring in any of these regions.

Existing codes also provide for the estimation of the total number of neutrons emitted from the outermost region included in the problem, again as a function of time and divided into several energy groups. Thus, these codes produce a "source term" for additional calculations of relatively low neutron fluxes further away from the explosive.

Low-flux Regions.--The most definitive work[5] which has been done to date on obtaining neutron fluxes external to the explosive involves the use of the neutronic codes mentioned previously. Instead of incorporating only the explosive geometry into the coordinate system used in the calculation, a large segment of the surrounding material (canister and rock, for example) are also considered. Thus, as the nuclear explosion proceeds, the interaction of the surroundings with the explosive is treated, and a more accurate assessment of neutron capture times and neutron energies at the time of capture can be made. Figure 1 shows the temperatures existing around an explosive as a function of time after detonation. Despite the obvious advantages of this computational approach, it can be put to only limited use due to the large amount of computer time required to obtain results. Thus, this method is used only to obtain some guidance on the behavior of specific devices; for subsequent parameter studies (such as activation of different varieties of rock) the neutron output from a conventional explosive calculation is coupled with a Monte Carlo[6] code which is used to estimate time-integrated neutron fluxes in various regions surrounding the explosive. However, by using the appropriate results regarding explosive configuration and environmental temperature obtained from the preceding more rigorous calculations, the simplified procedure can yield valuable and reasonably accurate results in only a fraction of the time required for the more sophisticated calculation.

COMPUTATION OF CROSS SECTIONS FOR NEUTRON-INDUCED REACTIONS

Although a large number of experimentally-determined cross sections and excitation functions are available for neutron-induced reactions (see Refs. 7 and 8), neutron cross sections for those nuclides that are involved in the multiple reactions occurring in high-flux regions are not easily measurable, and are not available at this time. Hence, appropriate codes are under development to calculate these needed cross sections.

The computation of (n, 2n) reaction cross sections, using a normalized statistical model approach,[9] has been generally quite successful. Although there have been no experimental checks of the validity of this cross-section calculational approach on those nuclides far from stability, the use of this model for two or three mass units on either side of the region of stability should give satisfactory results.

Again, for the (n,α) reaction, a combination of statistical and empirical calculations[10,11] seems to provide adequate results. Since charged-particle emission in general competes rather poorly against de-excitation by neutron or photon emission, the reaction products are not formed in great abundance, and the accurate estimation is not as critical (at least where gross gamma field predictions are concerned) as is the case for the (n,2n) and (n,γ) reactions.

The (n,p) reaction can proceed not only by means of the compound nucleus, but also through charge exchange (direct interaction). Thus, a theoretical treatment of this reaction becomes somewhat involved, and an empirical predictive method[12] is currently being used.

Of critical importance for the accurate calculation of neutron activation is an adequate predictive capability for (n,γ) reactions. Although these reactions have been studied in detail, both for the purposes of reactor and explosive design, as well as in the formulation of cosmological theory, recent evidence[13] indicates that serious gaps exist in nuclear reaction theory which makes extremely uncertain the prediction of (n,γ) cross sections by a theoretical approach. For the present, semi-empirical calculations are being used; however, work is continuing on a more adequate and reliable procedure.

ACTIVATION CALCULATIONS

High Flux Regions

Due to the incidence of multiple reactions in high flux regions, it has been necessary to develop "bookkeeping" codes to keep track of the build-up and depletion of individual nuclides in such regions. Essentially, the codes employ a calculated neutron flux (as obtained from a neutronic code output) at appropriate time intervals during the "burn" of fissile or thermonuclear fuel and, using the required neutron cross sections, calculate the nuclide composition within each region of interest as a function of time. The availability of an extensive nuclide "grid," as well as of a large library of neutron cross sections, allows the calculation of multiple reactions even on multi-isotopic elements. Figure 2 shows the multiplicity of cross sections which must be considered in a calculation of this sort.

Two major codes have been developed for this nuclide-accounting operation. The first, NOVA,[14] was originally written to obtain a predictive capability for heavy-element production in uranium targets subjected to intense neutron irradiation during the detonation of a nuclear device. It has since been rewritten slightly to allow its use with additional target elements.

The second code, ACT,[15] has been designed to utilize more of the neutron flux data generated by the neutronic codes in order to give a more accurate estimate of nuclide production in especially high flux regions. It also has the capability of calculating the radioactive decay of the various product radionuclides as a function of time.

Low Flux Regions

Since only single-order reactions are considered in such regions, a much simpler "accounting" code is required. For instance, there is no need to consider the build-up of nuclides as a function of time. Thus, the output of a Monte Carlo (or extended neutronics) calculation can be coupled with the appropriate compilation of neutron cross sections to obtain the desired list of radioactive species formed.

The ACTIVE code[16,17] has been developed to perform the above-described function; it also calculates the radioactive decay of the radionuclides formed. It has the capability of calculating simultaneously the activation products in all of the regions used in the Monte Carlo calculation and then producing a comprehensive compilation of radionuclides, automatically summing those produced in more than one region.

EXPERIMENTAL CHECKS

Limitations

An obvious test of the adequacy of the predictions obtained above may be made by comparing these results with measured values for radionuclide production. There are two principal difficulties that prevent the simple accomplishment of such a test. First, there are uncertainties in the total chemical composition of an explosive and of its environs. This is especially true of pre-1968 tests, where the need for careful sampling of device materials and soil had not as yet assumed its present importance.

Second, and more important, the chemical fractionation occurring in underground detonations is extreme for some elements, thus making an accurate estimate of the total production of certain radionuclides extremely difficult.[18-21] Consequently, although the calculational check obtained by examining experimental results may be at least semi-quantitative for the so-called refractory elements, data relating to the more volatile elements will probably be relatively unusable for such verification purposes.

RESULTS

Despite the difficulties outlined in the preceding section, some reliable experimental results have been obtained and are given (in a relative way) in Table I. It can be seen that, for the tungsten activation, calculated results are no worse than about a factor of two different from the measured values. It also appears that the predictive capability is improving; i.e., Event No. 3 shows a much better correlation between prediction and measurement than did the preceding Nos. 1 and 2.

Considering the more refractory elements produced mainly in the canister and soil, it can be seen from Table I, that here, too, the predicted production numbers are generally within a factor of two of the observed production.

As more adequate estimates of neutron cross sections become available, it is probable that significant improvement can be achieved in the ability to predict accurately a radionuclide source term.

CALCULATIONAL RESULTS AS RELATED TO UNDERGROUND ENGINEERING APPLICATIONS

Gas Field Stimulation

In the Gasbuggy experiment, a 26-Kt thermonuclear explosive was detonated in a gas-bearing rock; the resulting gas produced from this well contained 18μCi/ft^3 of tritium.[22] This relatively high concentration of total tritium in the produced gas was somewhat lower than the predicted value; however, it emphasizes the need to reduce the tritium production in Plowshare underground engineering explosives which are to be used for gas well stimulation.

Calculations[23] have been carried out for the Gasbuggy Event, allowing the emergent neutrons to impinge on Lewis shale.[24] This work indicates that as much as 1 g of tritium[25] will be formed from the ^{6}Li(n,α)T reaction taking place in the surroundings. Should 30 cm of boric acid be interposed between the neutron source and the shale environment, total tritium production will be reduced by a factor of about 100; about half of this tritium is produced in the soil, while the other half results from the ^{10}B(n,t)2α reaction taking place in the boric acid shielding.

Another source of tritium which cannot be neglected is the ternary fission process; approximately 0.0001 g is formed per kiloton of yield[26] (or a similar amount to that produced in the surroundings by a shielded explosive).

The actual concentration of tritium present in the gas produced from an environment resulting from the detonation of an explosive having such a low tritium yield cannot be specifically assessed; required inputs for a prediction include a detailed analysis of the detonation environment, including the characteristics of the in-place gas.

Ore Crushing

In the Sloop experiment,[27] a nuclear explosive is to be emplaced within a copper-bearing formation and detonated; the crushed ore will subsequently be leached with dilute sulfuric acid to remove and recover the copper.

Preliminary studies have indicated that one of the most troublesome radionuclides, in the sense of being difficult to remove from the copper during processing, is ^{106}Ru. Hence, it would seem that a thermonuclear explosive with relatively little fission would be the most desirable for use in this application. To date, induced radioactivities do not appear to present much of a problem with respect to the copper purification process. Possibly the most significant impact of using a thermonuclear explosive would be the appearance of tritium in the leach solution and hence, in the copper recovery plant. In order to meet occupational safety standards, it might well be necessary to conduct the refining operations in containers which are sealed or appropriately vented to a distant location.

GENERAL CONSIDERATIONS

It can be seen that, on the basis of the preceding instances, each potential Plowshare application must be carefully evaluated with regard to the production and distribution of radioactivity. As a result of this analysis, the appropriate combination of nuclear explosive and shielding will be chosen, the optimum product treatment or recovery plant will be designed, and appropriate research will be initiated to ensure that the product will conform to accepted radiological safety standards.

REFERENCES

1. L. E. Weaver, P. O. Strom, and P. A. Killeen, *Estimated Chain and Independent Fission Yields for Several Neutron-Induced Fission Processes,* USNRDL-TR-633, U. S. Naval Radiological Defense Laboratory, San Francisco, California (March 1963).

2. R. C. Bolles and N. E. Ballou, *Calculated Activities and Abundances of* U^{235} *Fission Products,* USNRDL-456, U. S. Naval Radiological Defense Laboratory, San Francisco, California (August 1956).

3. E. H. Fleming, Jr., *The Fission Product Decay Chains(*Pu^{239}*) with Fission Spectrum Neutrons,* UCRL-50243, Lawrence Radiation Laboratory, Livermore (1967).

4. D. W. Dorn, "Mike Results--Implications for Spontaneous Fission," Phys. Rev. *126,* 693 (1962).

5. R. W. Gell, *Neutron-Induced Activity in the Gasbuggy Event: A Geometry and Temperature Parameter Study,* UCID-15347, Lawrence Radiation Laboratory, Livermore (July 1968). (SRD)

6. E. F. Plechaty, *SORS: A Monte Carlo Neutron Transport Code,* UCRL-12193, Lawrence Radiation Laboratory, Livermore (January 1965). (SRD)

7. R. L. Macklin and J. H. Gibbons, "Neutron Capture Data at Stellar Temperatures," Rev. Mod. Phys. *37,* 166 (1965).

8. W. E. Alley, R. W. Gell, and R. M. Lessler, *Semi-empirical Neutron-Induced Cross Sections,* UCRL-50484, Lawrence Radiation Laboratory, Livermore (August 1968).

9. S. Pearlstein, "Analysis of (n,2n) Cross Sections for Medium and Heavy Mass Nuclei," Nucl. Sci. Eng. *23,* 238 (1965).

10. N. K. Majumdas and A. Chatterjee, "14.8 MeV Neutron Activation Cross-Section Measurements of a few Tellurium Isotopes," Nucl. Phys. *41,* 192 (1963).

11. E. Saetta-Menichella, F. Tonolini, and L. Tonolini-Severgnini, "Statistical Model Analysis of (n,α) Reactions," Nucl. Phys. *51,* 449 (1964).

12. R. M. Lessler, private communication.

13. A. Gilbert and S. G. Thompson, private communication.

14. D. W. Dorn, J. Georgatos, and L. Maizitis, private communication.

15. F. W. Guy, private communication.

16. F. W. Guy, private communication.

17. R. M. Lessler and F. W. Guy, *Gamma Dose Rates and Integrated Doses from Neutron-Induced Residual Radioactivity in Soil*, UCRL-12339, Vol. I, Lawrence Radiation Laboratory, Livermore (March 1965).

18. N. A. Bonner and J. A. Miskel, "Radioactivity: Distribution from Cratering in Basalt," Science *150*, 489 (1965).

19. J. A. Miskel, *Sedan Final Report: Radiochemical Analysis*, PNE-231F, Lawrence Radiation Laboratory, Livermore (1967). (SRD)

20. M. D. Nordyke and M. M. Williamson, *The Sedan Event*, PNE-242F, Lawrence Radiation Laboratory, Livermore (August 1965).

21. H. G. Hicks and G. W. Barton, Jr., *Chemical Fractionation of Underground Shot Debris*, UCRL-12227, Lawrence Radiation Laboratory, Livermore (December 1965). (SRD)

22. C. F. Smith and F. F. Momyer, *Gas Quality Investigation Program Status Report for Project Gasbuggy*, UCRL-71314, Rev-1, Lawrence Radiation Laboratory, Livermore (September 1968).

23. A. Gilbert and R. W. Gell, private communication.

24. J. H. Hill, private communication.

25. F. Holzer, Tritium Production in Underground Engineering Explosions, UCRL-71576 (Abstract), Lawrence Radiation Laboratory, Livermore (February 1969).

26. E. N. Sloth, D. L. Horrocks, E. J. Boyce, and M. H. Studier, "Tritium in the Thermal Neutron Fission of Uranium-235," J. Inorg. Nucl. Chem. *24*, 337 (1962).

27. P. F. Zimmer and M. A. Lekas (Eds.), *Sloop*, PNE-1300 (June 1967).

Table I. Relative radionuclide production from three Plowshare explosive tests.

	Atom Ratio: $\frac{\text{Measured}}{\text{Predicted}}$		
Nuclide[a]	Event No. 1	Event No. 2	Event No. 3
^{181}W	0.4	0.4	0.8
^{185}W	0.6	0.5	1.1
^{187}W	2.3	0.9	0.7
^{188}W	1.3	1.0	1.1
^{24}Na	1.1	---	---
^{32}P	0.6	---	---
^{51}Cr	0.4	---	---
^{54}Mn	0.7	---	---
^{55}Fe	0.6	---	---
^{59}Fe	0.5	---	---

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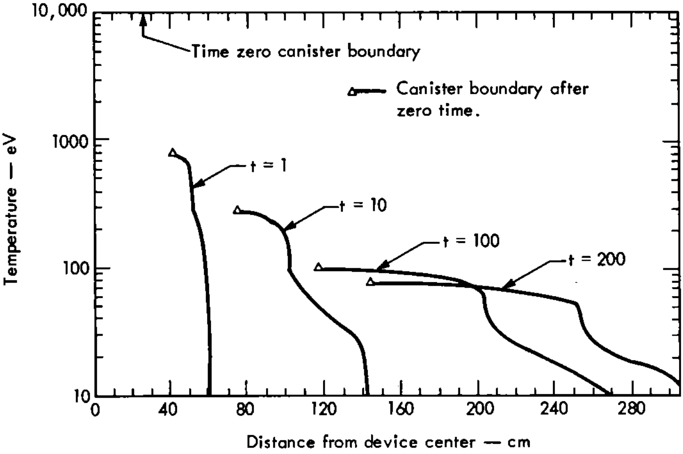
[a] The tungsten radionuclides were mainly produced in high-flux regions of the explosives; the other radioisotopes were principally formed in lower-flux regions.

FIGURE CAPTIONS

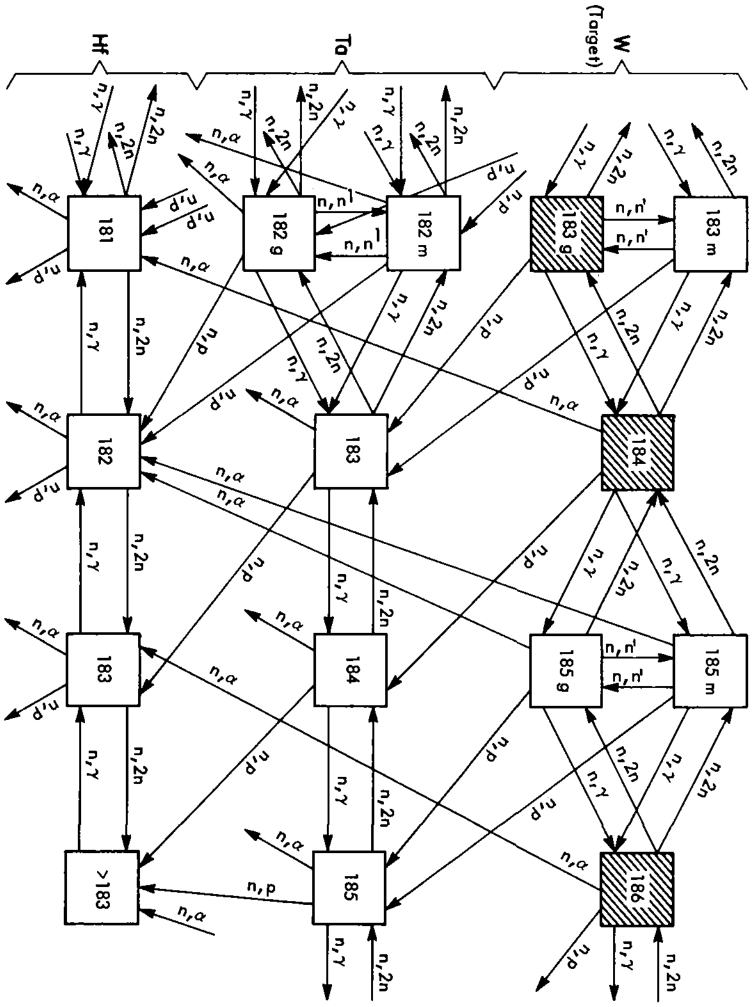
Fig. 1. Temperature/distance profiles for various relative times after start of nuclear burn, from the neutronic calculations.

Fig. 2. Principal nuclear reactions to be considered in ACT calculations (using a portion of the tungsten nuclides as an illustrative case). Cross-hatched blocks represent stable nuclides; open blocks represent radionuclides.



10,000
1000
100
10
Temperature — eV
0
40
80
120
160
200
240
280
Distance from device center — cm
Time zero canister boundary
Canister boundary after zero time.
t = 1
t = 10
t = 100
t = 200

Tewes - Fig. 1



Tewes - Fig. 2

QUESTIONS FOR HOWARD TEWES

1. From Charles Bowman:

With regard to available information, how accurately can krypton-85 and tritium inventories be assessed?

ANSWER:

Well, the answer to that is if you are talking about total production, I think that the krypton-85 total production, if you know the fissile material and the neutron spectrum, you could probably get the total production to better than 10%, I would guess. As far as tritium is concerned, that's a little trickier. I would say about a factor of two on that. But in general we try to err on the side of safety. In other words, we will predict it on the high end rather than what we think is the median.

2. From Charles Bowman:

How accurately can tritium produced from lithium-6 in alpha reactions be predicted?

ANSWER:

Well, this is largely a matter of judgment because you see our predictions are just that, we've never really been able to measure this in an explosion environment, I would have to say that, in view of the uncertainties and cross sections and neutron fluxes, I would say like a factor of three.

3. From Charles Bowman:

What is the critical configuration of lithium-6 about the emplacement point?

ANSWER:

The lithium-6 is in shale to the extent of a few parts per million so presumably it's sort of uniformly distributed around a detonation. Of course, if a detonation is taking place in some sort of a layered environment, this might not necessarily hold.

4. From Frank Lowman:

What would be the fission yield from naturally occurring fissile material in black shale from a 100 kiloton shot based on your calculated neutron fluxes in the soil?

ANSWER:

This depends on the amount of fissile material in the soil naturally. I went through this once, I forget for precisely what yield. I think it was of the order of 100 kilotons and I think the total yield that we were calculating was something of the order of a ton or a few tons. That's tons now not kilotons. That's natural uranium and, I guess, thorium also in the soil.

5. From Antonio Carrea:

Assuming a shot in a foreign country, could an independent safety analysis be done without declassifying information?

ANSWER:

At the present time, no.

METEOROLOGICAL REQUIREMENTS AND OPERATIONAL FALLOUT PREDICTION TECHNIQUES FOR PLOWSHARE NUCLEAR DETONATIONS

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ABSTRACT

Meteorological support requirements for Plowshare nuclear detonations are shown to depend on a number of factors. The importance of adequate support to the effective planning and safe conduct of a nuclear detonation is described. An example of the influence of atmospheric conditions on radioactive cloud development and local transport and fallout of radioactive debris is presented. Prediction of the future state of atmospheric wind structure, required for fallout predictions, depends on an adequate definition of its initial state and its rate of change. This definition, in turn, is shown to depend on an upper wind-sounding network of appropriate station density. An operational technique currently used for nuclear cratering fallout predictions is described and shown to produce results of useful accuracy.

INTRODUCTION

The measurement and prediction of certain atmospheric phenomena are vital to the effective planning and safe conduct of a nuclear detonation. Effective planning requires a timely evaluation of local climatology in order to anticipate the probable influence of atmospheric conditions on detonation effects and operational procedures. The ability to avoid undesirable effects from radioactive fallout resulting from a nuclear cratering detonation depends in part on the validity of the fallout prediction technique employed and the capability to predict meteorological input to the technique. The continuing development of improved prediction techniques requires adequate definition of those atmospheric parameters affecting the fallout process so that detailed post-detonation analysis can be performed.

It is reasonable to assume that future users of nuclear explosives for peaceful applications will be greatly concerned with economy. Undoubtedly the various types of support activities, including meteorological services, will be closely examined in order to reduce or eliminate as much of the effort as possible. No attempt will be made here to establish specific meteorological requirements since these will vary from one type of detonation to another. Rather, I will attempt to describe some of the considerations in determining support requirements, the importance of an adequate upper wind observational network, and the influence of atmospheric conditions on local transport and fallout of radioactive debris from nuclear cratering detonations.

CONSIDERATIONS IN DETERMINING SUPPORT REQUIREMENTS

The requirements for meteorological support depend on a number of factors. Important among these are the expected maximum credible release of radioactivity to the atmosphere and the human population distribution surrounding the detonation site. Geographical location, topographical features, proximity to bodies of water, operational procedures, and support contractor requirements all play a role in determining the extent of meteorological support.

Meteorological services may best be described by considering three phases in the conduct of a nuclear detonation. These three phases are arbitrarily called the preliminary, detonation, and post-detonation phases.

Preliminary Phase

It is during this phase that a detonation site is selected and organizations associated with the project are making plans for their participation. The location of on-site support facilities and instrument arrays to measure detonation effects are determined. An examination of climatological data at this time may reveal important atmospheric characteristics bearing on these activities. A knowledge of climatological wind direction frequencies, for example, may maximize the probability of obtaining needed radiological data. The unnecessary location of support facilities in the most probable fallout sector can be avoided. It is also important during this phase to examine climatological data in order to establish realistic meteorological restrictions under which the detonation is to occur. For example, clear skies may be desired in order that aerial photography may be obtained. A review of climatological data may indicate that certain wind flows are associated with clear skies, others with cloudy skies. If a choice exists, care should be taken to choose a sector for the placement of radiological sampling instrumentation which is consistent with a wind flow which climatology indicates is normally associated with clear skies. Another example would be the choice of a downwind fallout sector which is compatible with the desired long range radioactive cloud trajectory. Timely considerations of this type may result in the avoidance of costly delays or sacrifice of needed data. It is also during this phase that the meteorologist responsible for weather predictions during the detonation phase should be carefully studying climatological data. A meteorologist's predictive confidence should be tempered by a knowledge of the climatological probability of what he is predicting. If adequate climatological data are not available from an existing weather station, it may be desirable to obtain data at the detonation site far in advance of the detonation date. These data may be particularly important in understanding strictly local phenomena which will be discussed later.

Detonation Phase

It is during this phase that the nuclear detonation takes place. The safe conduct of a detonation requires accurate meteorological observations and predictions in order to avoid undesirable detonation effects such as excessive air blast overpressures and excessive radioactive fallout in populated areas. It is also during this phase that the collection of important radiological data takes place. The acquisition of these data is in part dependent on adequate meteorological predictions.

Meteorological information normally provided in support of a nuclear detonation is illustrated schematically in Figure 1. Sea level pressure, a sequence of upper air streamlines, and other charts not illustrated provide background information on current conditions. Panel 1 shows the predicted streamline flow at a particular altitude above mean sea level (MSL) for the time of detonation. Panel 2 depicts the predicted shot-time winds at the surface and at various levels (MSL) above the surface; while Panel 3 presents expected wind changes as a function of time. A predicted temperature profile (solid line) over the detonation site is in Panel 4 and a change with time (dashed line) is indicated. Panel 5 illustrates the predicted local fallout sector and hotline location; while Panel 6 shows predicted long range air parcel trajectories that are useful to indicate areas which are expected to be traversed by air potentially containing radioactivity. The predicted maximum external gamma exposure from radioactive fallout is presented by means of an exposure versus distance curve illustrated in Panel 7. Clouds and precipitation conditions, especially along the expected path of the radioactive cloud, are portrayed in Panel 8.

Prediction of the future state of the atmosphere depends upon an adequate definition of its initial state and an understanding of the changes taking place. The required initial state and rate of change can be obtained from an appropriate three-dimensional observational network. The network must have a station density, areal extent and observational frequency appropriate to the scales of atmospheric motions involved.

Post-Detonation Phase

It is during this phase that many diagnostic studies are performed. Some of these studies involve the use of meteorological observations obtained during the detonation phase. The evaluation of a fallout prediction technique, for example, requires a detailed analysis of the vertical wind structure affecting the fallout process. The wind structure observed only at the time and location of the detonation is inadequate to fully describe the local fallout process, which may have a duration of many hours and be affected by both time and space variations in wind structure. Since the validity of a fallout prediction technique depends on its ability to reproduce observed radiological fallout data, the collection of comprehensive radiological and meteorological data are important to continued improvement in prediction capability.

Upper Wind Observational Network Requirements

Let us examine upper wind network requirements by considering scales of motion[1] existing in the atmosphere. Atmospheric motions range in magnitude from the very small scale of molecular motion to the very large scale of planetary wave motions. Scales of motion affecting the transport of a radioactive cloud beyond the local area may be adequately defined in some areas by existing observational networks (e.g., the Weather Bureau's network across the United States). In other areas, such as over the oceans, existing observational networks may be inadequate. The station density of the upper wind sounding network in the western United States is shown in Figure 2. The average distance between stations is roughly 200 miles. A scale of motion defined by this network is called the synoptic scale. It contains such features as migratory wind systems with wavelengths on the order of 600 to 1,500 miles.

A smaller scale of motion, called the mesoscale, contains wind systems which can exist between stations in the network just described and be undetected by it. A denser network is required to define adequately the location and movement of these systems. An example of this scale of motion and its definition by synoptic and mesoscale observational networks is shown in Figures 3 through 7. The mesoscale network was established in support of a nuclear reactor experiment conducted 25 June 1965, at approximately 1800Z. Figure 3 shows a synoptic scale streamline analysis of the 8,000-ft. MSL wind flow at 1200Z. (The use of 8,000-ft data is not unique to the discussion; other levels could have been used.) At this time no unusual features are apparent. Figures 4 and 5 show two possible interpretations of the 8,000-ft. MSL flow 6 hours later (1800Z) at reactor run time. (Synoptic wind data are normally available at 6-hr. intervals.) A disturbing aspect of the analysis shown in Figure 4 is the location of a cyclonic circulation in an area of moderately strong wind speeds, since the speed at the center of the circulation must be zero. An analysis of the same data, shown in Figure 5, indicates the possibility of an anticyclonic circulation west of the Yucca Flat weather station (UCC) at the Nevada Test Site. Hourly wind soundings were obtained during this period at station UCC. The wind shift from south to north occurred at 1500Z. Winds remained northerly through run time, shifting back to the south one hour after the run. If the UCC soundings alone were available to supplement the synoptic data, one would be hard pressed to provide a satisfactory explanation of what had produced the shift. A wind prediction for run time would be even more difficult. The analyses shown in Figures 6 and 7 include data from the mesoscale network. The analysis in Figure 6 corresponds in time to that in Figure 3 and clearly indicates the presence, even at that time, of a disturbance in the wind flow not apparent on the synoptic scale analysis. Knowledge of its presence could be very important to test safety even though its movement may be unpredictable. Several hours advance notice of this disturbance was obtained as a result of the mesoscale network. The analysis in Figure 7 corresponds in time to those in Figures 4 and 5. It would appear from this analysis that the interpretation shown in Figure 5 was the better of the two synoptic scale analyses. An analysis of hourly data obtained from the mesoscale network indicates that the anticyclonic circulation moved southward into the network, then eastward, and finally recurved toward the north, exiting the network. At this time winds over the area returned to a southerly flow. It is clear that supplementation of a synoptic scale network with a single wind sounding station at the testing site can be woefully inadequate. It is likely, in this case, that, had an even denser or more extensive network been employed which might have resulted in earlier detection and better definition of the mesoscale circulation, even better meteorological advice could have been available. The problem is to achieve a realistic balance between desired prediction accuracy and the desire to minimize expenditures.

Certain mesoscale features of atmospheric motion are of purely local origin.[2] Although the presence of these local features can be anticipated, they change from day to day and from one location to another. Their detailed description and potential effect on detonation safety may require wind observations not available from an existing network. A familiar example of a local wind is the land-sea breeze found in coastal areas. Diurnal variations in low level winds result from the differential heating and cooling of the atmosphere over the sea and land surfaces. During the day a wind blows from the sea extending as far as 30 to 40 miles inland in temperate zones and to even greater distances in tropical regions. At night a weaker wind blows from the land out to sea extending on the order of a few miles. Both land and sea breezes are generally shallow phenomena, restricted to the lowest few thousand feet, but depths of 6,500 ft. have been observed. If a coastal site is chosen for a nuclear detonation, it is important that this mesoscale feature and its diurnal variations be understood and its possible effects on detonation safety be examined.

A second example of a local circulation which can be anticipated is the mountain-valley wind. This wind system is similar to the land-sea breeze in that it has diurnal oscillations with winds blowing upslope during the daytime and downslope at night. If a detonation site is chosen in mountainous terrain, this wind system and its diurnal variation should also be understood and its possible effect on detonation safety be considered.

Smaller scale turbulent motions exist which are exhibited as higher frequency wind fluctuations than those discussed above. Although these motions can produce some effects in the local fallout process, their size is small relative to the size of the radioactive cloud and therefore they do not affect its path appreciably.

Atmospheric Influence on Local Transport and Fallout of Nuclear Debris

Numerous examples of the effect of the various scales of atmospheric motion on airborne pollutants can be found in the literature. An interesting example of the effect of vertical temperature and wind structure and the influence of topographical features on the local transport of a radioactive cloud resulted from the recent Schooner cratering detonation at the Nevada Test Site. The supplemental upper wind network established for Schooner is shown in Figure 8. All available manpower and equipment were utilized in support of this experiment, resulting in a relatively dense network of observations. The locations of upper wind sounding stations (pibal and wind-finding radar) and temperature sounding stations (GMD), as well as the locations of aircraft temperature soundings (NATS), are indicated. The vertical temperature and wind structures observed at certain of these locations are shown in Figure 9. All temperature soundings were taken at detonation time. The times of wind observations correspond within an hour to the time of arrival of the peak radioactivity at distances comparable to the observation locations. The significant features of these observations are the presence of a low level temperature inversion and a corresponding discontinuity in vertical wind structure. The temperature sounding nearest the detonation site (U20B) shows the base of the inversion approximately 1,800 ft above surface ground zero. This inversion layer slopes upward as we proceed north to Site C (65 miles from ground zero) with its base being found approximately 2,400 ft above the elevation of surface ground zero. The corresponding discontinuity in vertical wind structure is clearly evident. The effects of these features on the Schooner debris cloud are also evident. Figure 10 is a schematic cross-section[3] (preliminary) of the Schooner cloud at the time of initial stabilization which occurred a few minutes after detonation. Both a main cloud and a base surge cloud are indicated. A comparison of altitudes of the top of the base surge cloud and the base of the aforementioned temperature inversion indicates that the inversion layer was effective in limiting the vertical development of the base surge cloud. The corresponding vertical wind structure shown indicates southeasterly to southerly winds below the inversion layer and south-westerly to west-southwest winds above. The effect of this discontinuity on the Schooner cloud is shown in Figure 11. This figure is a schematic representation of the peak dose rates observed near ground level during cloud passage. Only relative intensities are indicated. This pattern clearly shows that the base surge cloud was transported generally toward the north; whereas the main cloud was transported toward the northeast. To my knowledge, the vertical extent of the base surge cloud was never higher than the inversion layer as it was transported northward. Another interesting feature is the apparent "shadow" in the pattern, presumably caused by the combined effects of limited vertical development of the base surge cloud and the channeling of low level winds by the mountain ridge which reaches 9,500 feet MSL, extending well into the inversion layer. This example clearly illustrates the requirement for an adequate three-dimensional observational network if accurate prediction of the local transport of a radioactive debris cloud is desired.

The most important meteorological input required for the prediction of local fallout is an accurate prediction of the wind structure through which the particles will fall. This implies not only a requirement for the prediction of shot time winds but also their time and space variations. Other atmospheric phenomena are potentially important to the local fallout process. Vertical motions such as those observed within mountain lee waves[4,5] and convective activity (thunderstorms)[6], have velocities which are significant when compared to the terminal velocities of fallout particles[7]. In addition, the potential for precipitation scavenging must be recognized. If these phenomena cannot be realistically taken into account in fallout predictions, their interaction with the radioactive cloud should be avoided. If interaction cannot be avoided, potential "hot spot" areas should at least be delineated so that radiological monitoring can be conducted and appropriate safety measures taken if required. Determination of the location and intensity of these atmospheric phenomena depends on an adequate observational network probably including the use of weather detection radar.

An Operational Fallout Prediction Technique for Nuclear Cratering Detonation

A number of methods have been developed by various organizations for the prediction of local fallout. They employ similar fundamental considerations and reflect varying degrees of sophistication. One such method was that originally developed by the Special Projects Section, U. S. Weather Bureau, in 1955,[8] based primarily on fallout data from tower shots in Nevada. The total amount of fallout and the distribution of activity as a function of particle size and height in the initial radioactive cloud must be specified in order to predict a downwind pattern of fallout intensities. (A computerized version of this method is available.) A modification of this method[9] is currently being employed for the prediction of fallout intensities resulting from nuclear cratering detonations. Time does not permit a detailed description, however the major features will be described. This modified method provides predictions of hotline radiation intensities required for operational application. It is a scaling technique which does not require explicit definition of the distribution of activity as a function of particle size and height in the initial radioactive cloud. Rather, the assumption is made that an appropriate analog event can be chosen whose particle size-activity distribution will adequately approximate that of the event for which a prediction is being made. The scaling method consists of a simple ratio technique whereby the parameters which determine the hotline exposure rates and the location of these exposure rates in their respective fallout patterns are related, and then used in conjunction with the empirical results of a previous event for prediction purposes. The exposure rate levels are normalized to one hour after the detonation at all downwind distances to account for radioactive decay. The form of the scaling equation, where the unprimed symbols refer to the analog event and the primed symbols refer to the forthcoming event, is as follows:

$$A' = A \ \frac{\theta}{\theta} \left(\frac{h}{h'}\right)^2 \left(\frac{V}{V'}\right)^2 \ \frac{f'Y'}{fY}$$

where:

A, A'	are the exposure rate levels as a function of distance along the fallout hotline for an H+l hour reference time.
θ, θ'	are the directional shears in the wind hodograph from the surface to the top of the radioactive cloud at time of stabilization.
h, h'	are the radioactive cloud heights at time of stabilization.
V, V'	are the resultant mean transport speeds from the surface to an appropriate altitude in the radioactive cloud.
f, f'	are fractions of the total activity produced which occur as fallout.
Y, Y'	are the fission or fission equivalent yields of the nuclear devices.

The exposure rate level (A'), when computed, is applicable at a downwind distance determined by the following equation:

$$X' = X \frac{h'}{h} \frac{V'}{V}$$

where:

X, X' are downwind distances along the fallout hotline.

The unprimed quantities are obtained for the analog event by an analysis of observed exposure rate levels, meteorological conditions, and radioactive cloud dimensions. All yields are obtained from the nuclear laboratory conducting the experiment. Estimates of h' and f' are made by the use of empirical relationships developed from data obtained in connection with previous nuclear cratering detonations.[10] The quantities V' and θ' are obtained from the wind predictions described earlier.

The value of a fallout prediction method can be determined by its ability to reproduce observed radiological fallout data from the actual release of radioactive material. Radiological and meteorological data have been obtained for a number of nuclear cratering detonations. Data from several of these are presented to demonstrate the validity of the fallout scaling technique. The Sedan, Teapot Ess, Johnnie Boy, and Danny Boy observed hotline H+1 hour fallout gamma exposure rates as a function of distances are shown in Figure 12. Danny Boy was fired in hard rock while the others were fired in alluvium. The range in total yield of these detonations is a factor of approximately 240. The range in fallout fraction is a factor of approximately 13. Observed wind speeds, shears, and cloud heights, as expressed in the scaling equations, also varied considerably. Each of these curves has been normalized to a common set of conditions to provide a test of the scaling technique. The results of this scaling normalization are shown in Figure 13. If it were possible to account for all the factors which contribute to the differences in exposure rates observed for the several events, the normalization would result in a single curve. Although this is not quite the case, it is apparent that the scaling technique performs remarkably well for this series of events. The assumptions which were made in the development of the scaling technique appear to account for the major differences in the radiation levels resulting from these cratering detonations. The technique satisfies the requirement for an operationally useful radiation prediction method that can be both rapidly and easily employed. The method requires the minimum of input information essential for any fallout prediction technique and depends realistically on the empirical results of previous detonations as criteria for radiation prediction.

SUMMARY

The use of meteorological data and services during the various phases of a nuclear detonation have been described in order to point out some of the more important considerations necessary in determining adequate meteorological support.

Prediction of the local transport and fallout of radioactive debris resulting from a nuclear cratering detonation depends not only on the validity of the fallout prediction technique employed but also on the ability to predict the future state of those meteorological parameters affecting the transport and fallout processes. Data from the Schooner detonation were presented to demonstrate atmospheric influence on the base surge cloud development and the local transport of radioactive debris. Prediction of the future state of the atmosphere depends on adequate definition of its initial state and the rate of change taking place. A case study presented demonstrates the requirement for an appropriate network of wind sounding stations in order to define the location and movement of mesoscale wind circulations important to local fallout predictions and nuclear detonation safety.

A fallout prediction technique for nuclear cratering detonations was briefly described. The technique provides predictions of useful accuracy and satisfies the operational requirements of being both rapidly and easily employed in the field.

REFERENCES

1. Glossary of Meteorology, R. E. Huschke (Ed.), American Meteorological Society, Boston (1959).

2. F. Defant, "Local Winds" Compendium of Meteorology, T. F. Malone (Ed.) pp 655-672, American Meteorological Society, Boston (1951).

3. R. F. Rohrer, Private Communication.

4. R. D. Reynolds, R. L. Lambreth and M. G. Wurtele, "Investigation of a Complex Mountain Wave Situation," Journal of Applied Meteorology, AMS, 7: pp 353-358 (1968).

5. P. Queney, et. al., "The Airflow Over Mountains" Technical Note No. 34, World Meteorological Organization, p. 20 (1960)

6. H. R. Byers, "Thunderstorms" Compendium of Meteorology, T. F. Malone (Ed.) pp 681-693, American Meteorological Society, Boston (1951).

7. J. E. McDonald, "Rates of Descent of Fallout Particles from Thermonuclear Explosions," Journal of Meteorology, A.M.S., 17: pp 380-381 (1960)

8. K. M. Nagler, L. Machta, and J. F. Pooler, Jr., "A Method of Fallout Prediction for Tower Bursts at the Nevada Test Site," U. S. Weather Bureau, Washington, D. C., June 1955.

9. F. D. Cluff and T. R. Palmer, "A Fallout Scaling Model for the Prediction of Gross Gamma Dose Rates from Earth Cratering Detonations," unpublished manuscript, ESSA, ARFRO, Las Vegas, Nevada, 1964.

10. H. F. Mueller, "Local Fallout and Diffusion of Radioactive Material," Technical Discussions of Off-Site Safety Programs for Underground Nuclear Detonations, NVO-40, U. S. A. E. C., pp 216-225 (1968).

QUESTIONS FOR HAROLD MUELLER

1. From C. Nelson:

How can an official state agency obtain information from the Weather Bureau about the cloud path and altitude of airborne fallout from an U.S. or foreign nuclear detonation?

ANSWER:

I suppose the best person to address that to would be Robert Thalgott. In addition to that, I think a lot of this information is being published. I think it is available in a number of publications in the U.S.

2. From M. Chessin:

In view of the extensive meteorological preparations made for the Schooner shot, how does it happen that increased fallout was detected in eastern Canada?

ANSWER:

The answer to that is simply because it was carried there by the wind.

3. From Dr. Rozzell:

Did I understand correctly that coastal areas and mountain valley areas are best as detonation sites because of fairly predictable diurnal wind patterns?

ANSWER:

No, sir, I was not trying to imply that. I was simply trying to give a couple of examples of local circulations that potentially could affect fallout predictions. These are a couple of those local circulations.

4. From Kenneth Kase:

Was the determination of the Schooner cloud cross-section made by observation of the visual cloud. If so, is this an accurate profile of the radioactive cloud?

ANSWER:

There were all sorts of measurements of the Schooner cloud both visual and by aircraft sampling. I'm not sure if someone is going to speak to this later or not, but certainly the cloud shape was determined in several fashions and in the final analysis will be a composite of these various types of measurements.

5. From George Collins:

   In general, to what elevation must the vertical temperature and wind structure be known for a typical Plowshare experiment? Is this a function of whether a surface or sub-surface detonation is involved?

   ANSWER:

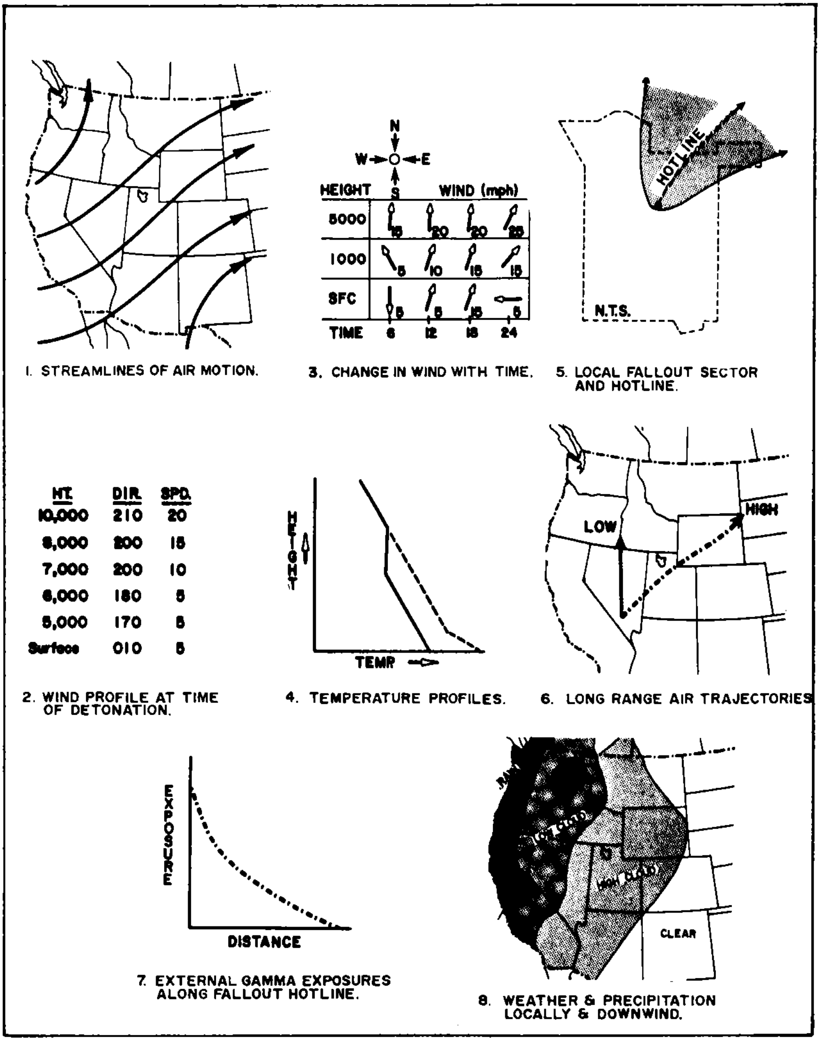
   Not really. Well, of course, we're not talking about surface detonations here. We are generally interested in the temperature structure up to quite high altitudes. One reason for this is as input to air blast predictions. But with regard to radioactive effluent predictions, it is not too different in terms of temperature sounding requirements whether we are talking about underground detonations or cratering events because the maximum credible accident assumed for an underground detonation usually implies that we will have a pretty decent sized cloud with dimensions not to dissimilar from a cratering detonation.

6. From H. Tewes:

   To your knowledge, was there any real evidence of advanced radiation levels in Canada resulting from Schooner?

   ANSWER:

   I heard there was, Howard, in the press. I haven't heard it from official sources, however.



1. STREAMLINES OF AIR MOTION.

2. WIND PROFILE AT TIME OF DETONATION.

3. CHANGE IN WIND WITH TIME.

4. TEMPERATURE PROFILES.

5. LOCAL FALLOUT SECTOR AND HOTLINE.

6. LONG RANGE AIR TRAJECTORIES

7. EXTERNAL GAMMA EXPOSURES ALONG FALLOUT HOTLINE.

8. WEATHER & PRECIPITATION LOCALLY & DOWNWIND.

Figure 1. Content of Typical Weather Briefing.

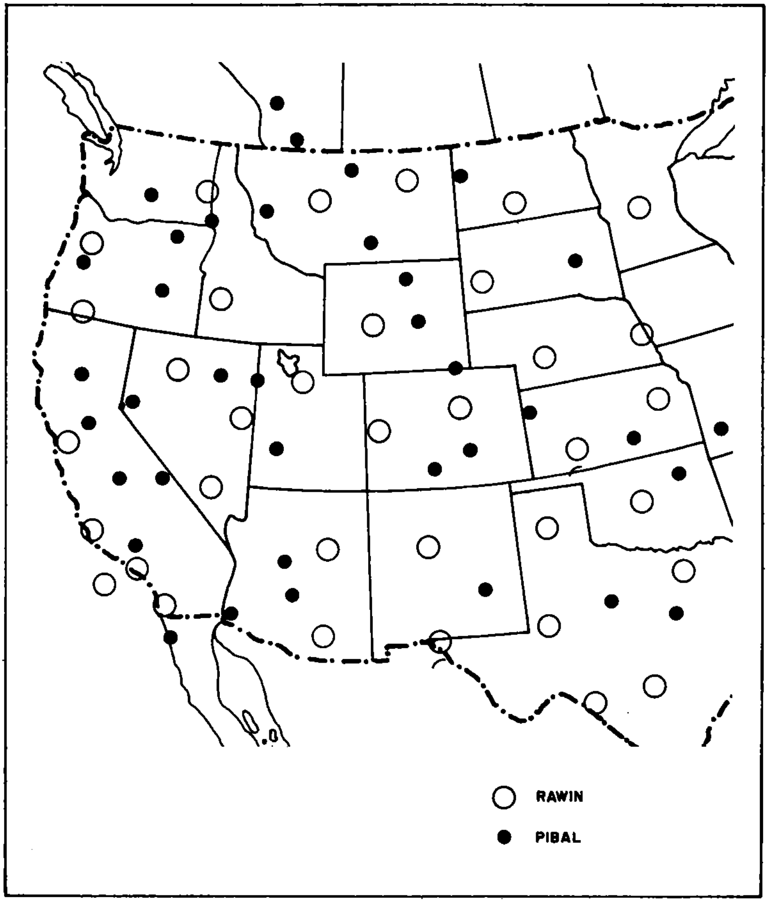


Figure 2. Upper Wind Sounding Network.

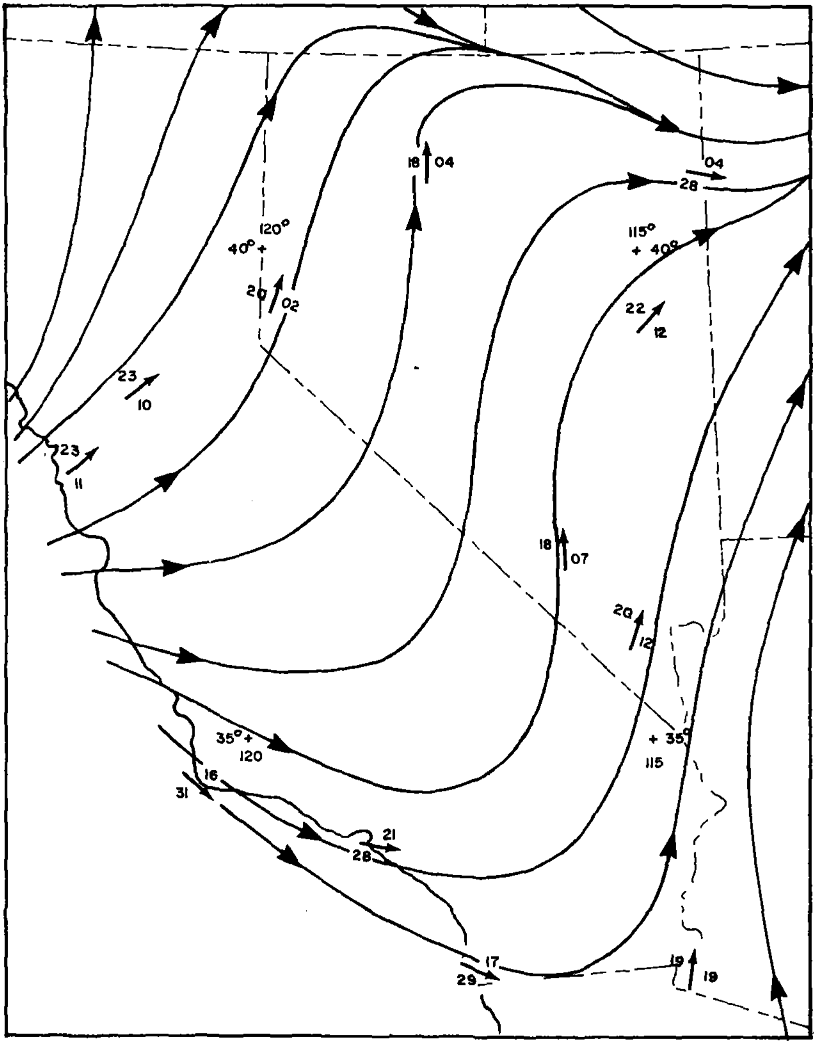


Figure 3. Streamline Analysis, 8000 Ft. MSL., 12 Z, 25 June 1965.

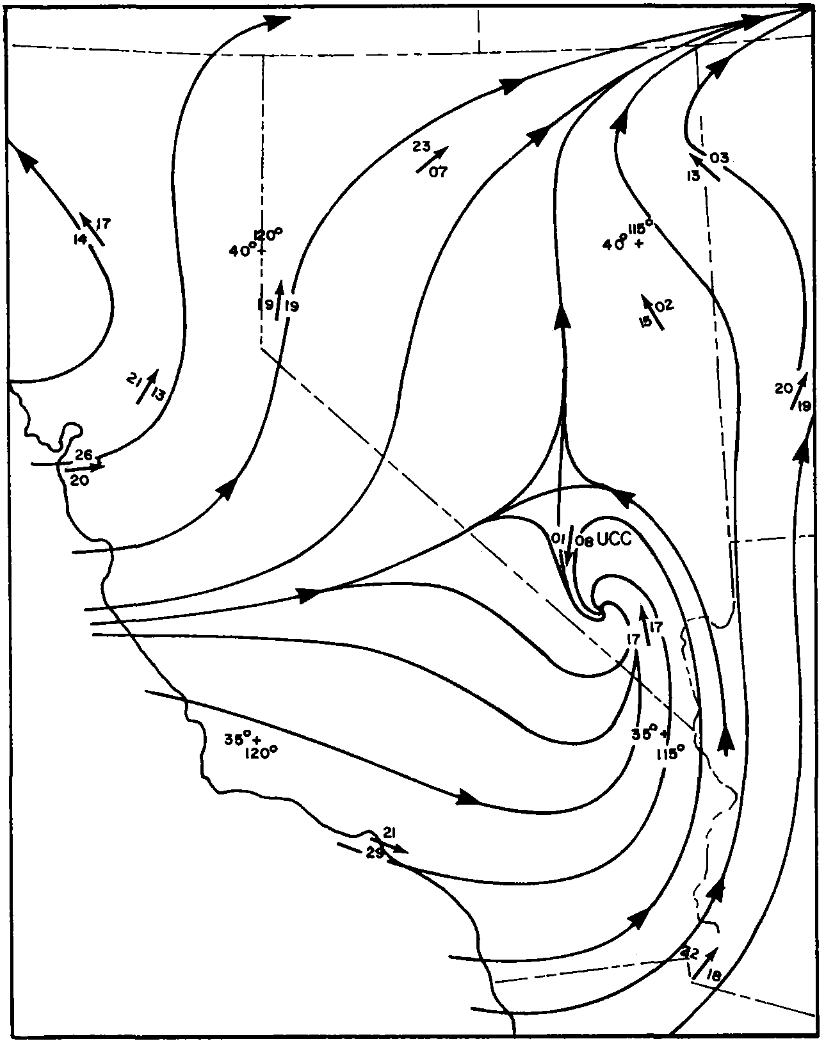


Figure 4. Streamline Analysis, 8000 Ft. MSL., 18 Z, 25 June 1965.

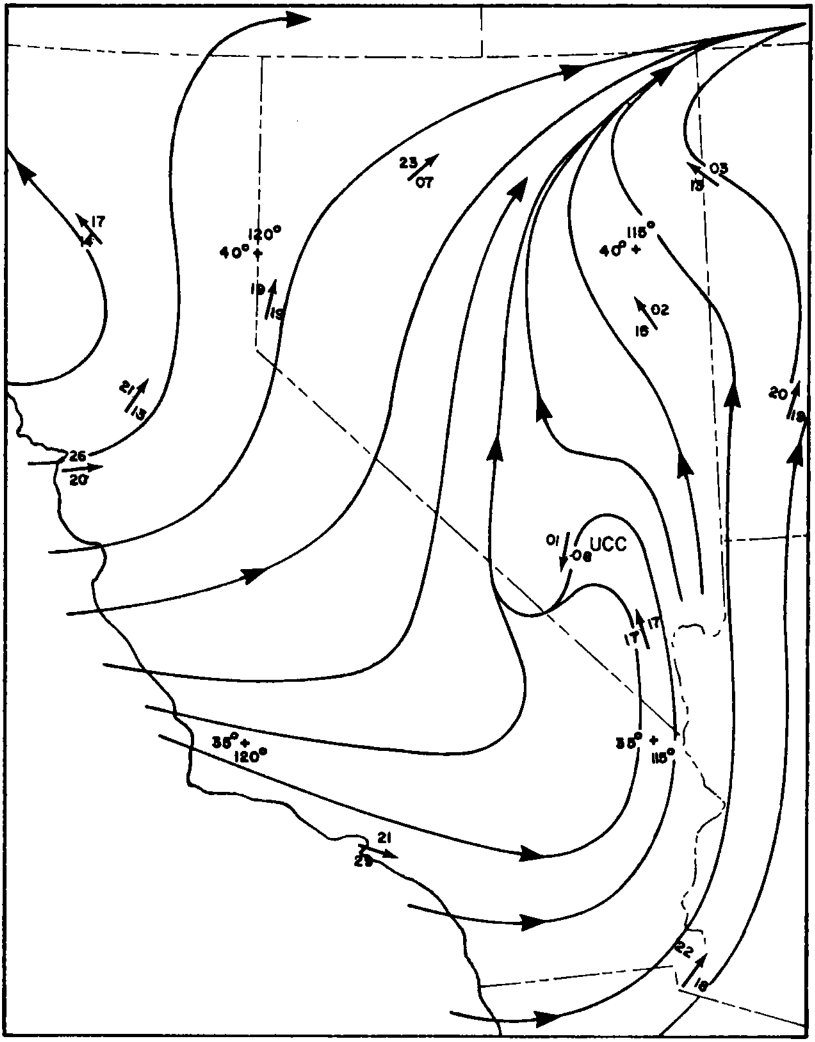


Figure 5. Streamline Analysis, 8000 Ft. MSL., 18 Z, 25 June 1965.

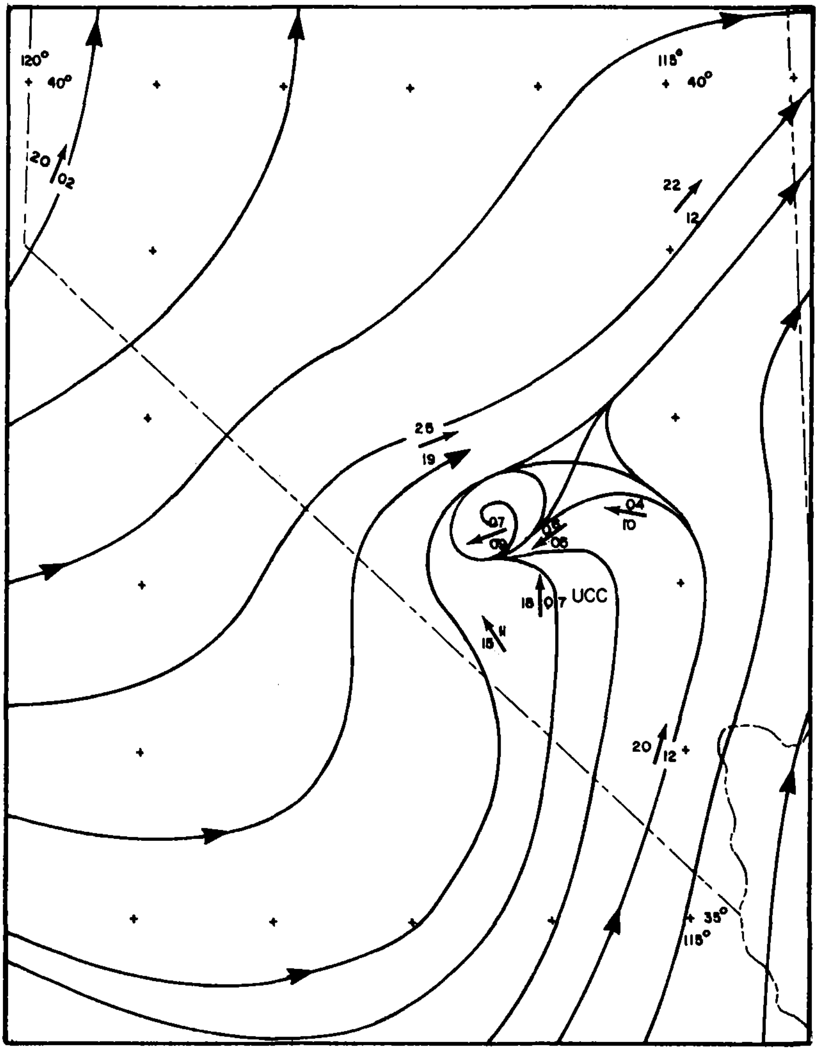


Figure 6. **Streamline Analysis, 8000 Ft. MSL., 12 Z, 25 June 1965.**

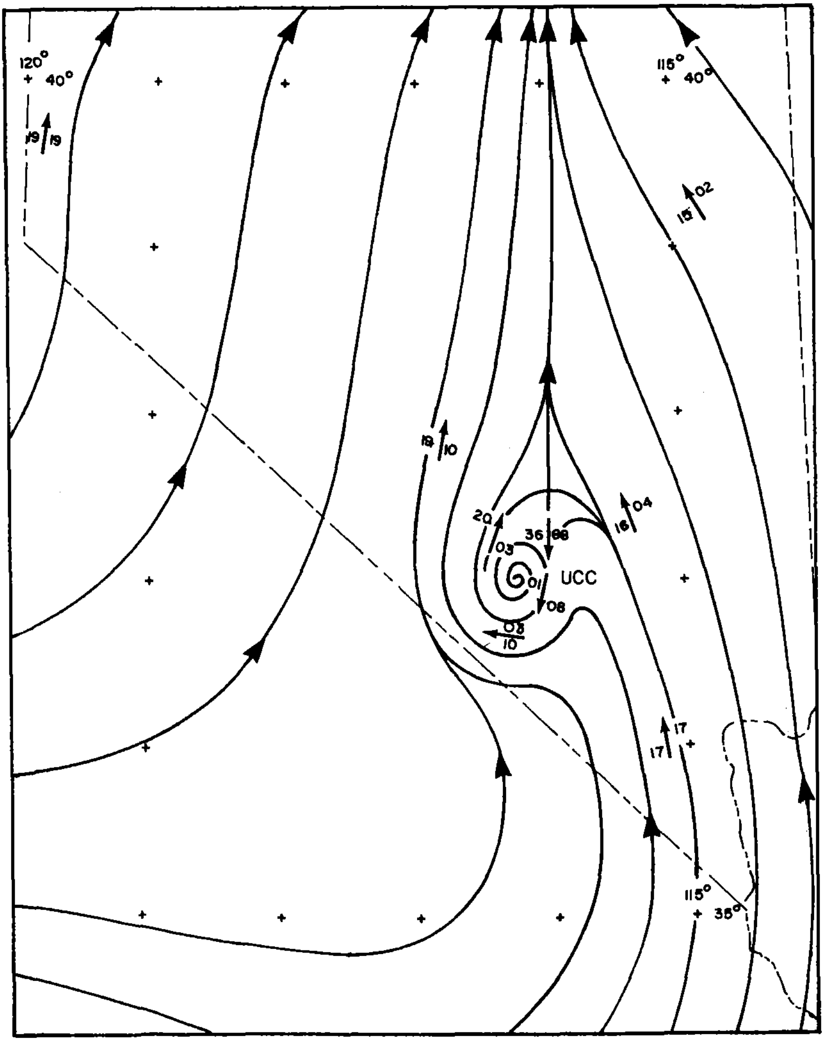


Figure 7. Streamline Analysis, 8000 Ft. MSL., 18 Z, 25 June 1965.

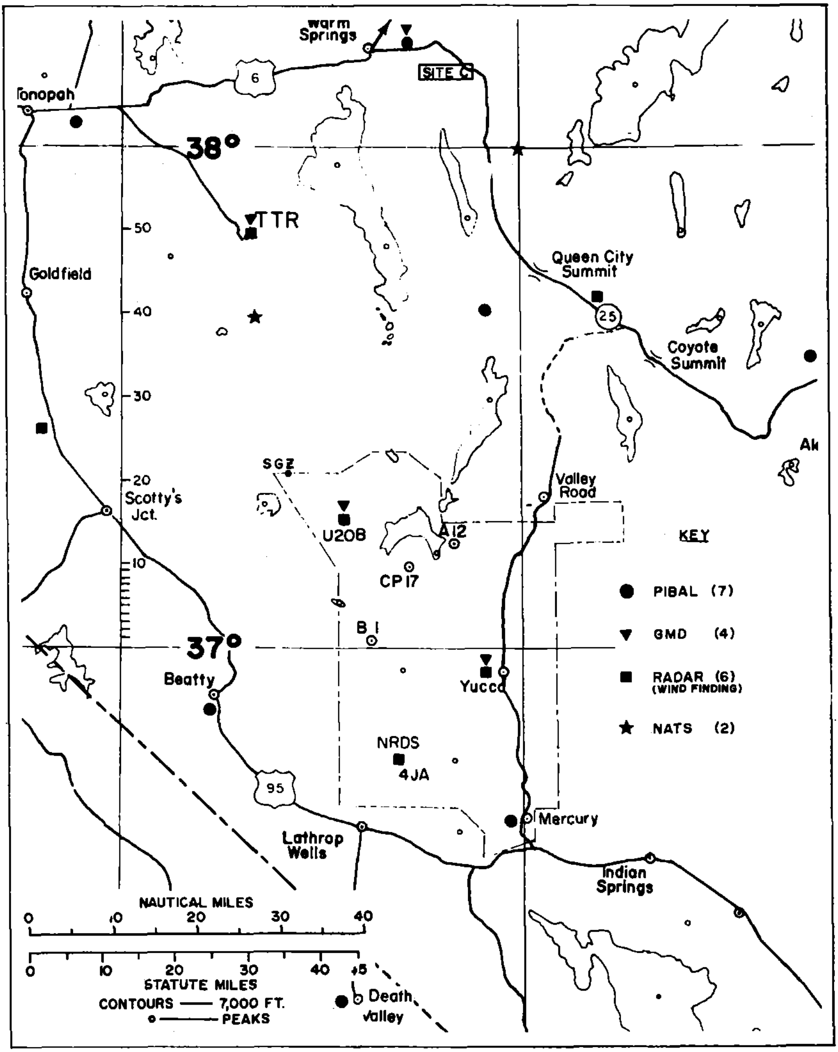


Figure 8. Schooner Upper Wind Sounding Network.

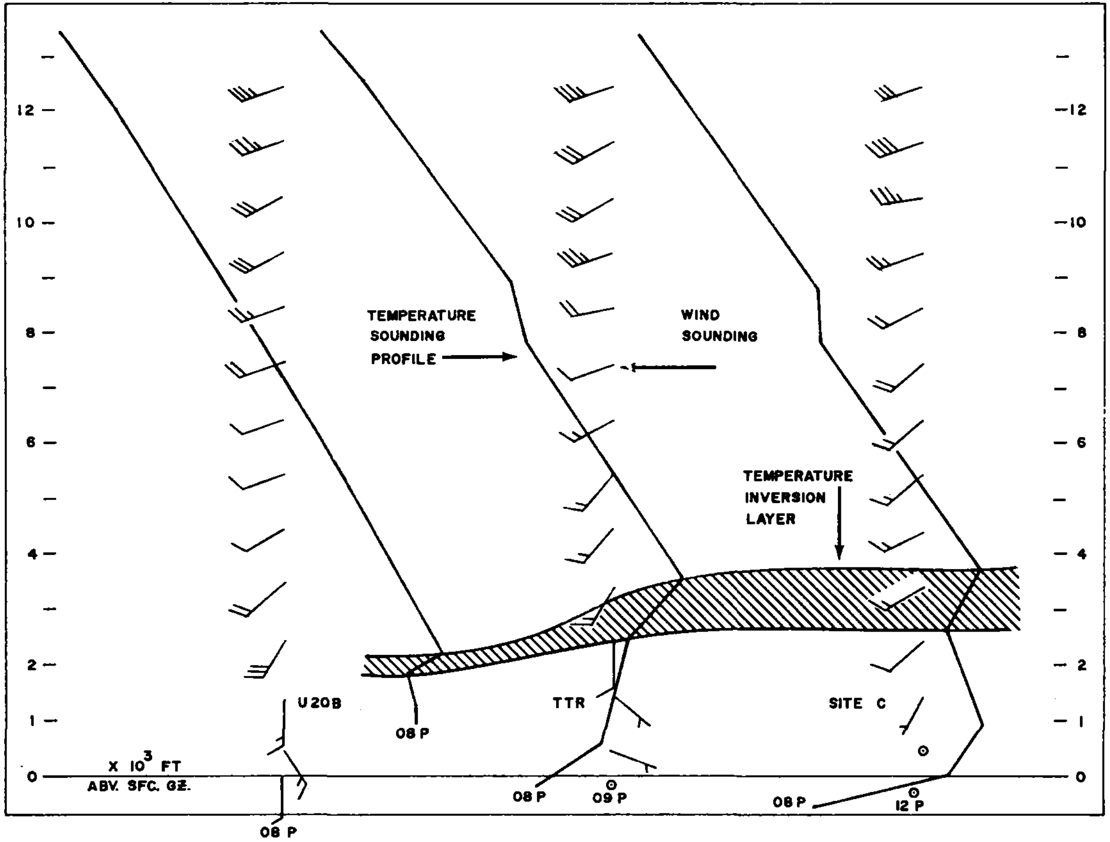


Figure 9. Wind and Temperature Soundings -- Schooner.

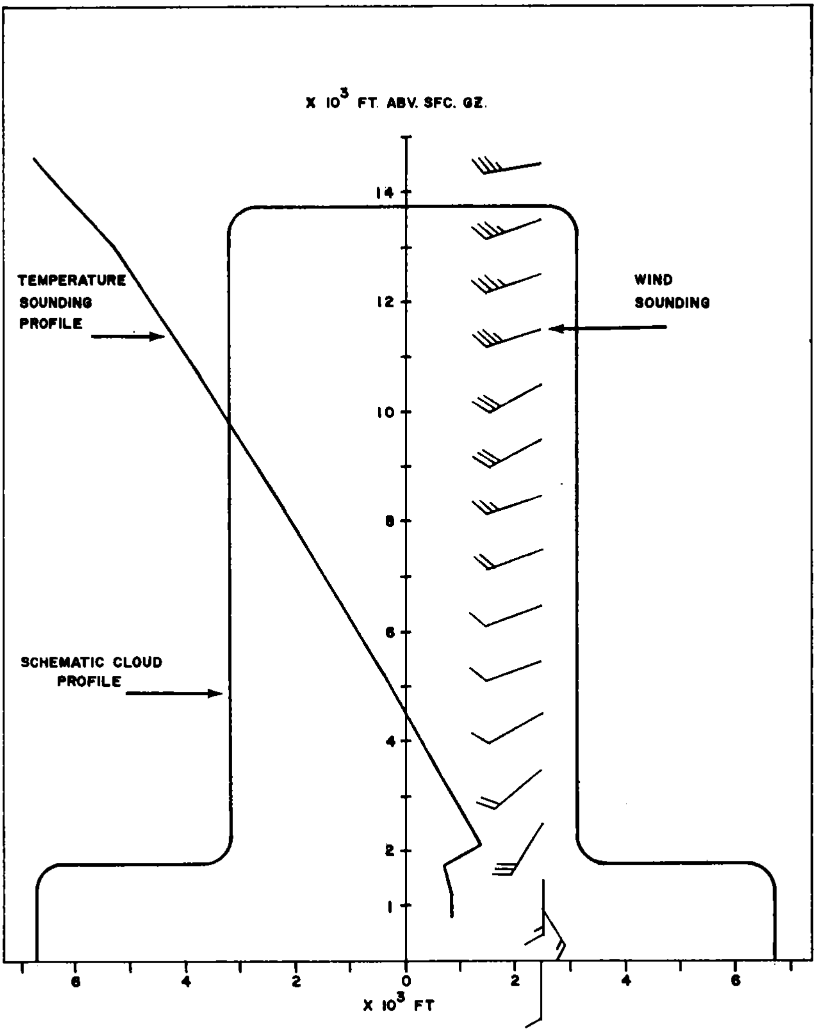


Figure 10. Schematic Cloud Profile -- Schooner.

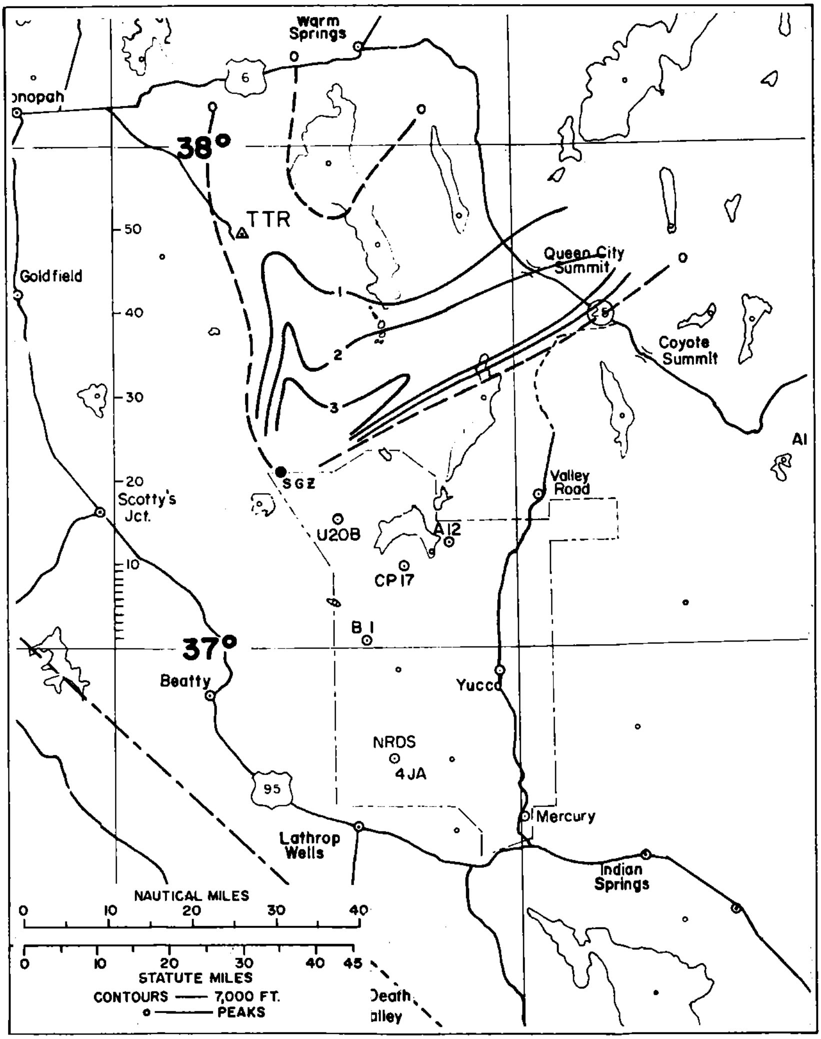


Figure 11. Schematic Dose Rate Pattern -- Schooner.

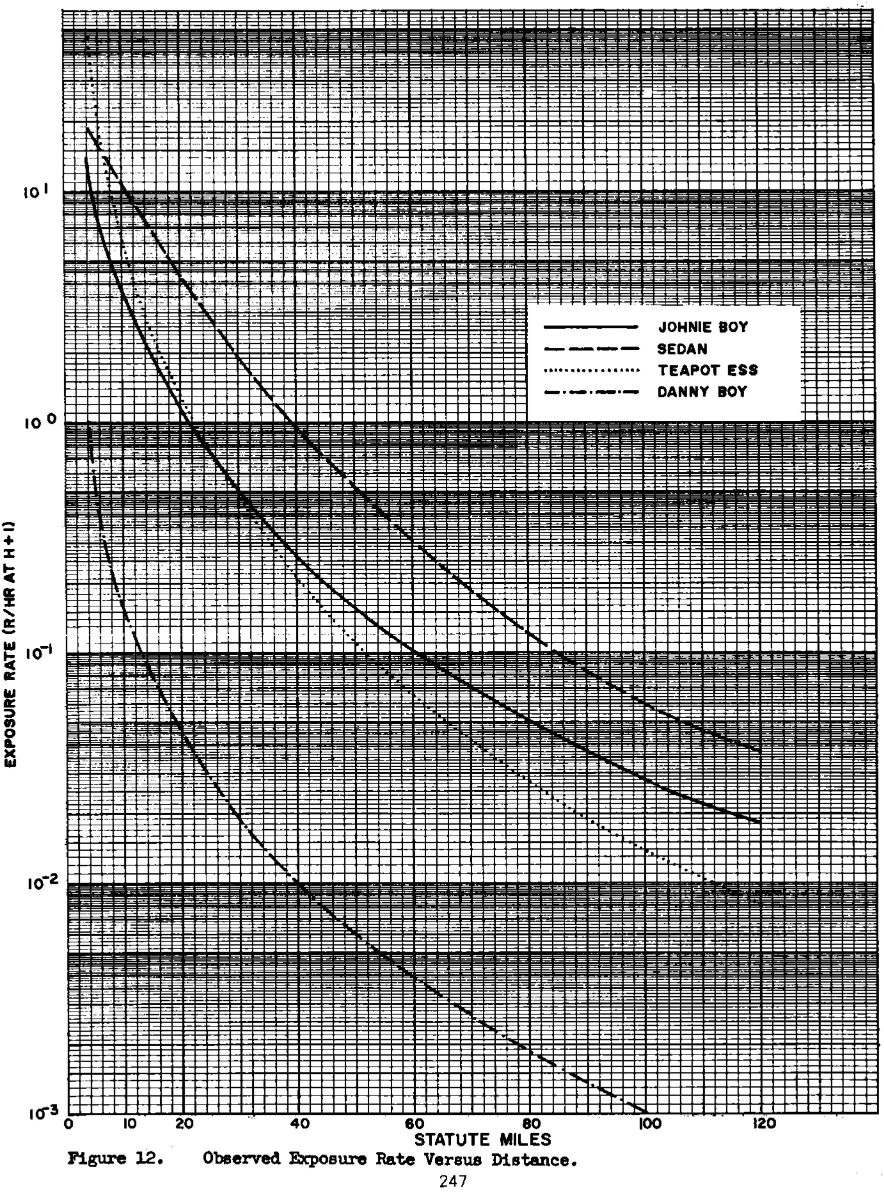


Figure 12. Observed Exposure Rate Versus Distance.

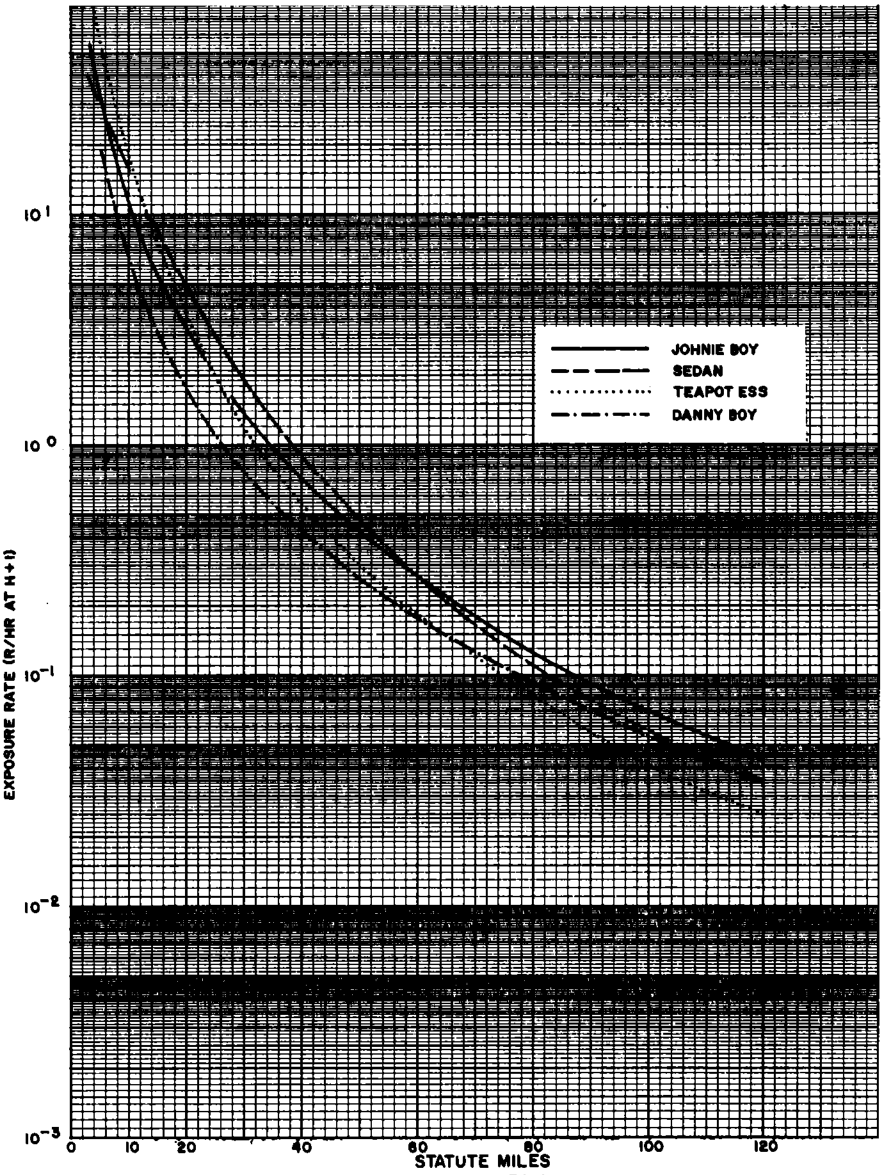


Figure 13. Normalized Exposure Rate Versus Distance.

ATMOSPHERIC TRANSPORT, DIFFUSION, AND DEPOSITION OF RADIOACTIVITY*

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ABSTRACT

From a meteorological standpoint there are two types of initial sources for atmospheric diffusion from Plowshare applications. One is the continuous point-source plume - a slow, small leak from an underground engineering application. The other is the large cloud produced almost instantaneously from a cratering application. For the purposes of this paper the effluent from neither type has significant fall speed. Both are carried by the prevailing wind, but the statistics of diffusion for each type are different.

The use of constant altitude, isobaric and isentropic techniques for predicting the mean path of the effluent is briefly discussed. Limited data are used to assess the accuracy of current trajectory forecast techniques.

Diffusion of continuous point-source plumes has been widely studied; only a brief review is given of the techniques used and the variability of their results with wind speed and atmospheric stability.

A numerical model is presented for computing the diffusion of the "instantaneously-produced" large clouds. This model accounts for vertical and diurnal changes in atmospheric turbulence, wet and dry deposition, and radioactivity decay. Airborne concentrations, cloud size, and deposition on the ground are calculated. Pre- and post-shot calculations of cloud center, ground level concentration of gross radioactivity, and dry and wet deposition of iodine-131 are compared with measurements on Cabriolet and Buggy.

INTRODUCTION

When a Plowshare device is detonated, a variety of radionuclides is produced in the underground environment. Depending on the

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*This work was performed under the auspices of the U.S. Atomic Energy Commission.

particular Plowshare application some of these radionuclides, particularly the more volatile ones, may be released to the atmosphere. In the case of cratering applications, the majority of the vented radionuclides are attached to particulate matter and rapidly settle to earth. However, some of the material is either in the form of gases or in the form of particles which are too small to have any significant fall speed.

The purpose of this paper is to discuss methods of predicting the atmospheric transport, diffusion, and turbulent deposition of the material which does not have any significant fall speed. An assessment of the relative accuracies of current prediction techniques will also be made.

Trajectory prediction techniques are common to the effluent which might be released from an underground engineering application and from a cratering application. Thus, these will be discussed first. The diffusion and deposition of effluent from each application will then be discussed separately because the diffusion approach is different for each application.

TRAJECTORIES

The most common method of constructing a trajectory is the central tendency method. This method assumes that the wind field is invariant between times for which no data are available. The best available wind field analysis for the height of interest is used. This could be a streamline analysis or a contour analysis on constant pressure charts. Isotachs aid the analysis. To construct the trajectory, a point is moved along with the available wind field for a time period equivalent to the time between observation periods. This period of movement of the parcel is centered on the time of the analysis.

This central tendency method is one of many possible kinematic methods of constructing trajectories. However, this is about the easiest method to use, and various studies[1,2] have shown that there is little difference in trajectory accuracy among the various kinematic methods, when the accuracies are averaged over a variety of synoptic situations. In any one particular case, one kinematic method may be somewhat better than another.

There are also dynamic methods of constructing trajectories which compute the acceleration of the air parcel. However, these are not widely used because they are more laborious to construct, and they require a high accuracy in the wind and pressure fields. This latter is true because the calculated acceleration is a small difference between two fairly large terms. Consequently, dynamic methods are seldom used in routine trajectory forecasting.

If the trajectory being constructed is a "hind cast," wind maps prepared from observations are used; or if it is a "forecast," then prognostic charts of the wind field are used.

What methods can be used to check the accuracy of trajectory forecasting techniques? As it is the path of parcels of air containing pollutants that are of interest, the best measurement of the trajectory would be a continuous tracking of the air parcel. However, this is difficult to accomplish as it takes almost continuous aircraft tracking of a "tagged" parcel for several days. The tracked air parcels which can be compared to trajectory forecasts are almost nonexistent.

The next best method would be to track a constant level balloon or a constant density balloon. Constant level balloons have been flown at heights of 200-300 millibars and set so that they stay on a constant pressure surface. Constant density balloons, which are also known as tetroons, have been flown in the lower atmosphere, say from 12,000 feet down to a few hundred feet above the ground, and are designed to float on a constant density surface.

Another method which has been used to study trajectories has been to construct a trajectory from observed wind data and compare it to a constructed trajectory based on forecast data. Ironically though, when constant level balloon data have been available, the error in "hind cast" trajectories has been determined to be about the same as in forecast trajectories.[1,2]

Using trajectories from 11 balloon flights at 200 millibars during the period of August 1949 to March 1950, Machta, in an unpublished paper,[1,2] found an average error of 32% of the total trajectory length for an average trajectory length of 855 nautical miles (average flight duration 15½ hours). An Air Weather Service trajectory study at 300 millibars, for 76 cases, compared forecast trajectories to balloon data. This gave an average cross trajectory error of 19.5% and an average along trajectory error of 25.9%. This resulted in a net error of about 32.5%.[1] Moore[3] had an average forecast trajectory error of 23% of the total trajectory path for balloons designed to fly at 300 millibars. "Hind cast" trajectories prepared for 20 balloon flights, selected for good behavior, right altitude, etc., gave an average trajectory forecast error of 20% of the trajectory path length of about 1000 miles.

Trajectory computations can be easily done by computer. By linking a trajectory forecasting technique directly to one of the numerical weather prediction models run by the Environmental Scientific Services Administration (ESSA) at Suitland, Maryland, one has the advantage of using small time steps in the central tendency method. This is because the numerical weather prediction models step forward in time steps of 10 minutes to an hour, whereas, prognostic charts or observational data are usually only available in 12-hour increments. Hurbert et al[4] ran 11 comparisons, with constant level balloons floating at 300 millibars and 72-hour trajectory forecasts prepared by the equivalent barotropic model. The equivalent barotropic model does calculations at the 500-millibar surface, and then it is necessary to extrapolate upwind to 300 millibar in order to compare calculations to the path of the constant level balloons. The average error in these comparisons for flights of 72 hour duration was about 25% of the flight path length.

Coming down in altitude to the lower levels (10,000-12,000 feet), there is the trajectory study done by Allen, et al.[5] This study was done utilizing trajectories originating at the Nevada Test Site (NTS). For the period of about a year four different kinds of trajectories were prepared (or available) at NTS. They were:

(1) A 30-hour 700-millibar forecast which was linked to the output of the three-level baroclinic prediction model being run by ESSA at Suitland, Maryland.

(2) The duty forecaster at NTS routinely forecast 30-hour trajectories from NTS. During the first part of the test period, these were at 10,000 feet and during the second part of the test period they were at 12,000 feet. Although these forecasters did not have access to the numerically prepared trajectories, they did have access to the prognostic charts prepared at Suitland, Maryland.

(3) The duty forecasters at NTS routinely reconstructed 30-hour trajectories using observed wind data.

(4) Small clusters of tetroons were launched almost daily and tracked by radar as long as possible. The maximum tracking time was about 50 hours. In order to minimize the grounding of these balloons and to optimize their radar tractability in the rough terrain of northern Nevada, these balloons were flown at 12,000 feet.

Over a forecast time period of 6 to 24 hours, the standard vector deviation from the tetroon trajectory end point and the NTS forecaster-prepared trajectory end point was 55-60% of the total tetroon trajectory length. The same accuracy was obtained by the numerical forecast trajectories from Suitland. The reconstructed trajectories done by NTS meteorologists had a standard vector deviation from the observed tetroon trajectory of 36 to 57% of the tetroon trajectory path length.

Examination of the data also indicates that there is a 50% chance that the vector standard error will be less than 47% of the total path length for the forecast prepared by NTS forecasters.[5] For "hind casts" prepared by the NTS forecasters, there was a 50% chance that the vector error will be less than 26% of the total trajectory path. Generally, the "hind cast" trajectories were shorter in total path length than the observed tetroon trajectories. There is some rationale for believing that the tetroons, because they are restricted to constant density surfaces, will tend to move faster than air parcels which could move up and down more (see discussion at end of Reference 5).

It is a little surprising in all of these studies to see that the "hind cast" trajectories are not much better than the forecast. The sparseness of upper wind data would contribute to this. In particular, the terrain in northern Nevada and the Rocky Mountain states would have a significant effect on the path of the tetroons studied by Allen, et al.[5] The meteorologists at NTS attempted to allow for terrain effects on their forecasts for the first few hours of the trajectory. However, at late times they relied on ESSA prognostic charts from Suitland, Maryland. In these numerical models the terrain is grossly smoothed. This lack of terrain effect was also very evident in the numerically prepared trajectory forecast from Suitland. Terrain may also help explain why the average error between forecast and tetroon trajectories is like 50-60% for the Nevada studies, whereas for the constant level balloons at higher altitudes the error was 20-30%.

It is also true that long trajectories and smooth "flow" tend to have less percentage error. The smooth flow makes the lack of spacial resolution in the data less critical. Long trajectories also tend toward a more climatically averaged transport speed.

A low-level trajectory study done by Peterson[6] compared tetroon trajectories at 500-1000 feet above the ground, with reconstructed trajectories using an adjusted surface wind, a surface geostrophic wind, a second standard level wind, and a 5000-foot wind. The trajectory construction technique in all cases was the central tendency method. The basic tetroon data was a card mailed back from wherever the tetroon was found. Thus the landing point was known, but not necessarily the path between launching and landing.

Out of these data it was possible to show that the reconstructed trajectory using the adjusted surface wind, adjusted for speed change with height and for veering with height, gave the best fit to the observed landing position of the tetroon.

All of these systems of reconstructing trajectories were unsuccessful in cases of rough terrain and in cases of interaction with frontal surfaces.

In reality it is necessary to deal with air parcels which follow isentropic surfaces. Isentropic surfaces may or may not coincide with isobaric or constant height surfaces.

In particular, isentropic surfaces are nearly parallel to frontal surfaces and thus air parcels rise over fronts. Routine isentropic forecasts were not and are not available to compare with observations of "tagged" air parcels. Isentropic "hind casts" have been used a great deal as a diagnostic tool; this is particularly true for stratospheric trajectories. The framework for isentropic trajectory forecasts is available,[7,8] but it needs to be put to routine use.

Lastly, in closing this discussion of trajectory forecasting it should be mentioned that ESSA currently runs a trajectory forecast program at the numerical weather prediction unit at Suitland, Maryland. The trajectory forecast uses a central tendency method and linear interpolation between the grid points used in six-layer primitive equation model.[9] At each hour during the computation of the 48-hour forecast, wind direction and speed is tabulated at each grid point and for a variety of heights. Trajectories are then prepared utilizing one-hour time steps and these forecast winds. Trajectories can be run at several different heights and with several different starting points. Unfortunately, a comparison of these computer trajectories with tetroon data or even reconstructed trajectories has not been done yet.

UNDERGROUND ENGINEERING APPLICATIONS

Most conceivable underground engineering applications would be done with the Plowshare device buried too deep for there to be any significant probability of a dynamic venting. If any venting occurs, it most likely will be in the form of a small continuous leak of volatile radionuclides. This effluent would be carried downwind by the local, near-surface wind pattern. The diffusion of this continuous plume of effluent would be well described by the Gaussian plume diffusion model. This model is represented by Equation (1):

$$\chi = \frac{Q}{2\pi\, \sigma_y\, \sigma_z\, u}\, e^{-1/2\left[\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]} \qquad (1)$$

Where:

χ = the concentration, pCi/m^3

Q = the source, pCi/sec

y = the crosswind distance from plume axis, m

σ_y = the standard deviation of the crosswind Gaussian distribution of concentration, m

z = the vertical distance from the plume axis, m

σ_z = the standard deviation of the vertical Gaussian distribution of concentration, m

u = the mean horizontal wind speed, m/sec

Various forms of Equation (1) have been well studied in the meteorological literature for the last 30 years. The books by Sutton,[10] Pasquill,[11] and the recent (1968) issue of Meteorology and Atomic Energy,[12] give good reviews of plume diffusion. For our purposes here, it is sufficient to say that one needs to know the leak rate, the wind speed, and σ_y and σ_z in order to evaluate Equation (1). If the leak is surface-based and if surface concentrations are desired, then $z = 0$ and Equation (1) is multiplied by two. Much of the discussion of this equation in the meteorological literature has hinged upon different ways of evaluating σ_y and σ_z as functions of atmospheric stability, wind speed, and distance downwind.

The most useful and realistic method of evaluation σ_y and σ_z is to use the many diffusion tests, which have been done over the years, to evaluate σ_y and σ_z as a function of distance under different atmospheric conditions. Thus, these standard deviations are empirically determined from concentration data for different meteorological conditions. Figures 1 and 2 give the variation of these parameters with distance and with atmospheric stability. This presentation of the data was originally done by Pasquill[13] in 1961. Concentration data obtained since then [12] still fits these categories.

Table 1 gives a qualitative description of the stability categories. This description was originally proposed by Pasquill.[13] These stability categories have also now been related to the standard deviation of the wind direction fluctuation when the sampling time for wind directions is about a half hour.[12] This relationship is given in Table 2.

This approach to evaluating the diffusion of continuous point sources has become standard practice. There is enough experience now with these nomographs to indicate that they work reasonably well when the time of effluent emission is long compared to the travel time to the sampler and when the time of plume passage past the arcs of samplers is about an hour or less. The reason for the latter comment is that almost all of the plume diffusion experiments have been done for sampling times of about a half hour to an hour. If longer sampling times were used in the experiments, the values of σ_y and σ_z on Figures 1 and 2 would be larger. In order to evaluate the exposure at some point downwind, the concentration should be calculated for averaging periods of about an hour. Wind direction data can then be used to determine how many hours the plume might be over a particular point downwind if periods of longer than an hour are involved.

CRATERING APPLICATIONS

The majority of the effluent which might be released by a cratering application would be released almost instantaneously and as a large volume source. This large volume source will be diffusing as it travels along its trajectory. Diffusion will be with respect to a coordinate system which moves with the large volume source. Hence the statistics of turbulent diffusion are considerably different for this source than they are for the continuous plume.

In classical diffusion theory, there are analytical solutions for an instantaneous point source. These result in a spherically symmetric Gaussian cloud or puff. However, these solutions are not applicable for the large volume sources that would be generated by a Plowshare cratering application. For instance, as time approaches zero in the instantaneous point source, the concentration goes to infinity. This implies an infinite exposure rate which is unrealistic. Yet, realistic estimates of early time exposure rates are needed.

Let us assume that the fraction of nuclides produced which are vented to the atmosphere is independent of the explosive yield. Then the initial cloud concentration, for those nuclides whose production is directly proportional to the yield, is independent of yield. This is because the initial volume of the volume source is almost directly related to yield.[14] Thus, as the yield increases the nuclide production increases and the initial volume, within which the effluent is distributed, increases in about the same proportion. Total exposure is dependent upon cloud passage time as well as upon concentration. Assuming a constant wind speed during cloud passage, the exposure time is directly related to a cloud dimension. Any one dimension of this initial volume source increases about as the cube root of the yield. Thus, as yield increases, total exposure experienced by an individual in the path of the effluent only increases as the cube root of yield.

For those nuclides whose production is independent of yield, the initial concentration is inversely proportional to the yield. The total exposure to this type of nuclide, from a passing cloud is inversely proportional to the 2/3 power of the yield.

After a day or two, when the effluent size is measured in the hundreds of kilometers, the effluent doesn't know what its original size was. Thus, the initial size associated with the effluent is not important when one is concerned about very late time concentrations.

Another reason that the classical diffusion theory instantaneous point source solutions are not applicable to large volume sources generated by Plowshare cratering applications is that analytical solutions require the assumption that the atmospheric diffusivity is independent of time or space. In fact, the rate of atmospheric diffusion is dependent upon the scale of the process and thus increases with time.

Therefore, at the Lawarence Radiation Laboratory (LRL) a numerical model was developed[15] which incorporates, in a rational way, what is currently known about atmospheric diffusion of large clouds.

The numerical model is two-dimensional; three-dimensional diffusion is obtained by assuming circular symmetry about a vertical axis. The basic differential equation to be numerically integrated is:

$$\frac{\delta\chi}{\delta t} = K_r \left[\frac{\delta^2 \chi}{\delta r^2} + \frac{1}{r} \frac{\delta\chi}{\delta r} \right] + \frac{\delta}{\delta z} \left[K_z \frac{\delta\chi}{\delta z} \right] \qquad (2)$$

where χ is concentration per unit volume, r is radial distance from the axis of symmetry, z is vertical distance, K_r and K_z are radial (or horizontal) and vertical diffusivity, respectively. Radial diffusivity is assumed to be independent of height, and vertical diffusivity is independent of radial distance from the cloud center. The diffusivities are determined by the turbulent properties of the atmosphere and the scale of the cloud.

The solution of Equation (2) is straightforward. The secret of success lies in the manner in which the horizontal and vertical diffusivities are specified as a function of time and space. In the numerical model being described here, the predictions of similarity theory as applied to atmospheric diffusion[16] are used to predict the horizontal diffusivity as a function of the cloud size and as a function of the turbulent properties (specifically the turbulent dissipation) of the atmosphere.

In the case of K_z, the similarity predictions for kilometer-sized clouds would result in unrealistic values used near the ground surface. Because there are much data on near-ground surface vertical diffusivities and some data on how these vary with height, it was decided to let K_z be an arbitrary function of height and time. This would also allow us to "mock up" the effects of temperature inversions in the free atmosphere on vertical diffusion. However, the computer code currently uses the simplified form of K_z as a function of height, as given in Figure 3. Therefore, K_z is allowed to increase linearly with height in the boundary layer and then is held constant with height until the top of the mixed layer is reached. It is implied that the environmental lapse rate is almost dry adiabatic to the top of the mixed layer. Above this height, vertical diffusivity is allowed to decrease with height until it reaches a prescribed "ambient value" for the free atmosphere. The depth of the boundary layer, the altitude of the top of the mixed layer, the altitude of the stable layer, the value of K_z at one meter above the ground, the value of K_z immediately above the top of the boundary layer, and the value of K_z above the stablizing inversion are all input parameters. In the current version of the numerical model these parameters along with time, altitude above mean sea level of the ground, height of the cloud center, atmospheric dissipation, and rainfall rates are read in as an input table. Thus, all of these parameters can be arbitrary functions of time. The numerical model interpolates linearly between values specified at discrete time intervals. It is obvious that all of these K_z parameters are not well measured for any one particular event. Nevertheless, it should be pointed out that all of the details of K_z which are so important for micrometeorological calculations are not as important for predictions of the gross characteristics of large volumes of effluent. By an examination of upper air temperature and wind data and judicious use of micrometeorological studies in the surface boundary layer, reasonable estimates of these turbulent parameters can be made for any particular event.

The geometry associated with the numerical model is depicted in Figure 4. As is evident from this figure, the numerical model assumes circular symmetry. This is a weakness in this particular model because it is not then possible to explicitly handle accelerated diffusion caused by persistent (in time) changes in horizontal wind speed and/or direction throughout the depth of the effluent.

There are several nondiffusive effluent depletion mechanisms included in the numerical model. Non-falling but near-ground surface effluent tends to deplete some of its material to the ground by impaction of submicron particles on vegetation or by absorption of gas by vegetation. In atmospheric diffusion problems, this form of depletion is usually handled by multiplying an empirically determined deposition velocity times the ground level air concentration. This results in a net flux of material toward the ground. Deposition velocities have been empirically determined for different radionuclides. The numerical model being discussed here uses this approach, with a deposition velocity being specified as an input parameter. As part of the concentration calculations, there results a ground-level concentration value. This is multiplied times the deposition velocity and integrated over time of cloud passage to calculate total deposited amount on the ground. The amount deposited is also depleted from the lower part of the cloud in this calculation.

Another nondiffusive depletion mechanism is precipitation scavenging. There are two forms of precipitation scavenging, one called washout and the other called rainout. Washout refers to the removal of particulate matter by rain drops falling through a cloud of particulates, colliding with the particles, and then carrying them on to the ground. Rainout refers to the condensation of water vapor on particulate matter and then their subsequent scavenging. The washout mechanism is the only one handled so far in this numerical model. Washout is dependent upon the precipitation rate and the particle size of the effluent being washed out. In calculations done with this numerical model, the precipitation rate is input as a function of time. The coefficients which are associated with particle size are put in at the beginning of a calculation. It should also be noted that the top of the precipitation scavenging can be independently specified in this numerical model.

The radioactivity decay of gross fission products as well as specific nuclides can be handled within this numerical model.

A typical calculation starts with the geometry of the stablized (motions which were initially responsible for producing the cloud are no longer important) cylindrical volume source and a Gaussian distribution of activity within this volume. Concentrations and deposition are calculated over the time period of interest, which may be several days, according to the input atmospheric turbulent parameters and nondiffusive depletion mechanisms along the effluent's trajectory. If the calculation is being performed in a diagnostic sense, after the event, then the meteorological parameters are those which are observed along the trajectory. If it is a calculation being done before the event, the along-trajectory meteorology may come either from climatology or from immediately pre-shot forecast meteorology.

Since the development of the numerical model, case studies are being done in order to see how well the model works against data. Before presenting some case study data, it should be noted that it is extremely difficult to obtain airborne concentration measurements with enough time and space resolution to determine the "representativeness" of each sample. In other words, was the sample taken within the majority of the effluent? In order to answer this question, much data are needed. It should be noted on the figures to follow that the concentrations are given in pCi/m^3 with the radioactive decay being included. It should also be remembered that normal atmospheric background has not been subtracted from these data and that this background value is about one pCi/m^3.

The NRX/EST EP-4A nuclear rocket engine test of March 25, 1966, was the first case study done. As such, no climatological or forecast calculations were done ahead of time. Thus, in Figure 5 we see the diagnostic calculation using the along-track observed meteorology and the measurements. All of the available aircraft data are plotted on Figure 5. It is obvious that much of the data was taken on the fringes of the cloud. An examination of the location of each filter sample with respect to the majority of the cloud also would lead one to this conclusion.[17] It should be emphasized that, on Figure 5 and on the figures to follow, an initial amount of radioactivity in the cloud and the along-track meteorology are used in the calculation. There is no attempt to normalize the diffusion calculations to the observed airborne concentrations.

Figure 6 shows calculations and data for the Phoebus IB-EP-4 nuclear rocket event of February 23, 1967.[18] In this case a climatological forecast was prepared ahead of time, using pre-event predictions for the radioactivity in the cloud and along-track climatology for the meteorology. There was no precipitation along this effluent trajectory, and the differences between the climatological and diagnostic prediction curves on Figure 6 are the result of differences in along-track turbulence. Again, all data available from aircraft are plotted on this figure. Thus, much of it is on the fringes of the cloud or just plain background levels. The altitudes of the effluent involved in Figures 5 and 6 were in the 8000- to 12,000-foot MSL range.

For the Plowshare cratering experiment, Cabriolet, of January 26, 1968, three different types of predictions were prepared. A climatological forecast using pre-shot estimates of airborne radioactivity was performed several weeks prior to execution. A forecast calculation was prepared using the pre-shot estimates for source term and forecast along-track meteorology as of about four hours prior to execution. Lastly, the diagnostic calculation has been prepared post-shot, using observed along-track meteorology and observed source term data for chemistry. These three types of calculations and the observations are presented in Figure 7. In this event the climatological and forecast calculations were made using the total amount of radioactivity expected; this would be related to exposure rate measurements within the effluent. This total included the gaseous products. The diagnostic calculation on Figure 7 was prepared using only the particulate activity. It is this particulate activity which would be collected on filters. This difference amounts to about a factor of two from H+1 to H+10 hours. At later times, say at H+50 hours, the contribution of the gaseous products to the total activity is negligible. This comment explains some of the difference between the forecast and climatological prediction and the diagnostic on Figure 7 at times of H+1 to H+10 hours.

The hollow symbols on Figure 7 are exposure rate measurements converted to pCi/m^3 with the assumption that the sample was taken in the middle of an infinite volume of effluent. The solid symbols are filter data. Only data which are considered to be reasonably representative of Cabriolet concentrations are presented in Figure 7.

The differences in the three types of predictions, which become apparent around H+10 hours, are the result of there being no precipitation in the climatological forecast, whereas, in the forecast calculation the precipitation was forecasted to start at about H+10 hours. In the diagnostic calculation, precipitation started at about H+8 hours. There is also some difference between the total amount of precipitation forecast and that observed.

Figure 8 gives the measured and calculated airborne concentrations for the Plowshare row-cratering experiment, Buggy, which was executed on March 12, 1968. The format of the data presentation is the same as was on Figure 7 except that all of the measurements are included. The climatological calculation is the only one presented here and it includes both the gaseous as well as particulate material. The forecast calculation is available, but there is little difference between it and the climatological and thus it is not added to the figure. Again, at times later than H+10 hours the contribution due to the gaseous is small compared to that due to the fine particulate matter. Thus, at these times the filter data can be directly compared to the calculation. A complete analysis of the Buggy event is not finished as of the time of the preparation of this paper. Therefore, no diagnostic calculation is presented for Buggy. However, it is not expected to differ by more than a factor of two or three from the climatological calculation presented in Figure 8. There was no significant precipitation along the trajectory of the Buggy effluent.

From these case studies it appears that the calculations made with the numerical model lead to airborne concentrations over time periods of a couple of days, which are within a factor of two of the measurements. This is considered quite good by this author when one considers the difficulty of numerical modeling on this time and space scale, and when one considers the dynamic range of 8-10 orders of magnitude involved in the concentrations.

A variety of other parameters are calculated with the numerical model. However, in the interest of brevity, only one other type of calculation will be presented here. This is a calculation of the deposition of material along the ground under the center of the volume of effluent. It must be stressed that this is not a fallout calculation. Deposition in this numerical model results from a turbulent impaction of submicron particles on vegetation, utilizing the empirical deposition velocity concept, and/or that material deposited by precipitation scavenging throughout the cloud. Figure 9 is such a deposition calculation for iodine-131 for Cabriolet. The data on this figure come from two sources: (1) Public Health Service (PHS) milk samples, and (2) material deposited on large plastic sheets which were located downwind and which are coated with a sticky substance. These data are probably only accurate to within a factor of two. The difference between the climatological and the diagnostic curves of Figure 9 at distances of 10-100 kilometers is one of source term. Pre-shot, seven to eight times more iodine-131 was expected to be vented than was actually observed. The other significant difference is the large peak in the diagnostic calculation about 400 kilometers downwind. This was a result of the interaction with snow shower activity in Cabriolet. The two milk samples above this hump were both collected in a "snow-out area." The remainder of the milk samples was presumably collected in areas for which there was no significant precipitation. The surface deposition data between 600 and 700 kilometers downwind was all snow data. The snow which fell on plastic sheets was bundled up and taken back to the laboratory for analysis. The range in values at this distance is the result of these samples being collected along a line which traversed the path of the effluent cloud. The hump in the climatological calculation at about 1000 kilometers is a result of depletion of effluent near the ground at night. On the next day vertical diffusion rates increase, more effluent diffuses down to near ground levels, and then the dry deposition increases.

Figure 10 is the iodine-131 deposition, calculations and measurements for Buggy. As the diagnostic calculations have not been performed, only the climatological one is presented here. There was no precipitation scavenging in Buggy.

In both Figures 9 and 10, all available data beyond about 100 kilometers are presented. Some locations are obviously closer to the path of the cloud center than are others.

SUMMARY

For the most part, trajectory predicting methods use wind data on isobaric surfaces and/or constant height surfaces and have accuracies of 20-60% of the total trajectory length over time periods of a day or two. Trajectories at low altitudes and particularly over rough terrain are the most difficult to forecast and have the worst accuracies in the above statistics. It is possible, however, to recognize meteorological situations which would result in a higher than average accuracy in trajectory predictions. A significant increase in trajectory forecasting accuracy, particularly at low levels, will probably not occur until observational data becomes available with more spacial resolution than is available now. For instance, the horizontal spacing between wind observation stations in the U.S. is around 300 kilometers.

Air parcels follow isentropic surfaces. As isentropic trajectories do not necessarily coincide with isobaric or constant height surfaces, it would be useful to perfect isentropic trajectory technique for routine use.

Although the mechanisms of turbulent diffusion are not yet well understood, there has been much experience with the use of Gaussian plume models to describe the diffusion from continuous point sources. Thus, in this paper only a brief review of the subject of diffusion from continuous point sources has been done. The only intent here was to show that such procedures do exist and to show how they are used.

The diffusion of almost instantaneously produced large volume sources of pollutants for time periods of a few days has not been well studied in the past. Thus, a major portion of this paper was devoted to discussing a numerical model, developed at LRL, of the large cloud diffusion processes. This numerical model uses the similarity theories of atmospheric turbulence for horizontal diffusion and permits the use of time- and height-dependent vertical diffusivities. Although not well vindicated for the diffusion of kilometer-size clouds, similarity theory predictions are consistent with the available atmospheric data.

The depletion of the cloud by ground deposition and precipitation has been included in the model, but the diluting effects of vertical shears in the horizontal wind field have not been included. Parameter studies indicate that the effect of any one atmospheric parameter is not too important on the long-term concentration calculations. However, the elimination of many of the real physical parameters in this model would have a significant effect on predictions. With the existence of such a numerical model, it is easy to perform sets of calculations with different possible real physical situations. This could give an expected range in concentration predictions for any particular application. Calculations using this numerical model for four case studies have indicated that accuracies of about plus or minus a factor of two in airborne concentration for time periods of a few days. The same range of accuracy is applicable to the long-range deposition calculations. It is satisfying to this author that these kinds of accuracies can be obtained with the model over such a period and over such a dynamic range in the concentration values.

REFERENCES

1. Air Weather Service, U.S. Air Force, "Constant-Pressure Trajectories," AWSM 105-47, Headquarters Air Weather Service, USAF, Washington, D. C., September 1956.

2. J. K. Angell, "Use of Constant Level Balloons in Meteorology," Advances in Geophysics, Vol. 8, pp. 137-219, (Academic Press, New York, 1961).

3. C. B. Moore, J. R. Smith, and A. Gaalswyk, "On the use of Constant Level Balloons to Measure Horizontal Motions in the Atmosphere," J. Meteorol. 11, 167 (1954).

4. W. E. Hubert, P. M. Wolff, and C. L. Cave, "A Comparison of JNWP Trajectory Forecasts with Transosonde Flights," Monthly Weather Rev. 86, 53 (1958).

5. P. W. Allen, E. A. Jessup, and R. E. White, "Long Range Trajectories," Proceedings of the U.S. AEC Meteorological Information Meeting, September 11-14, 1967, pgs. 176-190, published by the Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada as Report AECL-2787.

6. K. R. Peterson, "Estimating Low Level Tetroon Trajectories," J. Appl. Meteorol. 5 [No. 5], 553 (1966).

7. R. J. Engelmann and W. E. Davis, "Low Level Isentropic Trajectories and the Midas Computer Program for the Montgomery Stream Function," Battelle-Northwest, Richland, Washington, Report BNWL-441, April 1968.

8. J. D. Mahlman, "Numerical Methods of Computing Three-Dimensional Trajectories for Adiabatic and Diabatic Flows," Air Force Cambridge Research Laboratories, U.S. Air Force, Bedford, Mass., Report AFCRL-68-0357, August 1968.

9. F. G. Shuman and J. B. Hovermale, "An Operational Six-Layer Primitive Equation Model," J. Appl. Meteorol. 7 (4), 525 (1968).

10. O. G. Sutton, "Micrometeorology," (McGraw-Hill, New York, 1953).

11. F. Pasquill, "Atmospheric Diffusion," (D. Van Nostrand Co., Ltd., London, 1962).

12. U.S. Atomic Energy Commission, "Meteorology and Atomic Energy, 1968," U.S. Atomic Energy Commission Division of Technical Information, David H. Slade, ed., July 1968.

13. F. Pasquill, "The Estimation of the Dispersion of Windborne Material," Meteorol. Mag. 90, 33 (1961).

14. W. C. Day, "Cloud Dimensions for Cratering Explosions," U. S. Army Engineer Nuclear Cratering Group, Lawrence Radiation Laboratory, Livermore, *NCG Technial Memorandum No. NCG/TM66-8*, 1966.

15. T. V. Crawford, "A Computer Program for Calculating the Atmospheric Dispersion of Large Clouds," Lawrence Radiation Laboratory, Livermore, Report UCRL-50179, 1966.

16. G. K. Batchelor, "The Application of the Similarity Theory of Turbulence to Atmospheric Diffusion," *Quarterly J. Roy. Meteorol. Soc.* *76*, 133 (1950).

17. T. V. Crawford, "Long Range Diffusion of the NRX/EST EP-4A Effluent Cloud," Lawrence Radiation Laboratory, Livermore, Report UCRL-50299, 1967.

18. T. V. Crawford, "Long Range Diffusion of the Effluent Cloud from the Phoebus 1B EP-IV Reactor Test of February 23, 1967," Lawrence Radiation Laboratory, Livermore, Report UCRL-50418, April 1968.

Table I. Relation of turbulence types to weather conditions.

A -- Extremely unstable conditions
B -- Moderately unstable conditions
C -- Slightly unstable conditions
D -- Neutral conditions[*]
E -- Slightly stable conditions
F -- Moderately stable conditions

	Daytime insolation			Nighttime conditions	
Surface wind speed, m/sec	Strong	Moderate	Slight	Thin overcast or $\geq$ 4/8 cloudiness[†]	$\leq$ 3/8 cloudiness
<2	A	A - B	B		
2	A - B	B	C	E	F
4	B	B - C	C	D	E
6	C	C - D	D	D	D
>6	C	D	D	D	D

---

[*] Applicable to heavy overcast, day or night

[†] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

Table 2. Relationship between Pasquill stability categories and the standard deviation of the wind direction fluctuation over 30 minutes.

Pasquill stability categories	
A, extremely unstable	25.0°
B, moderately unstable	20.0°
C, slightly unstable	15.0°
D, neutral	10.0°
E, slightly stable	5,0°
F, moderately stable	2.5°

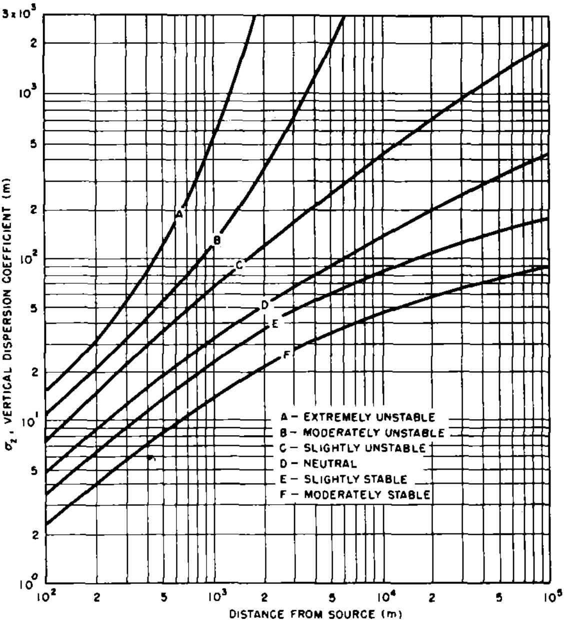


Figure 1. Vertical diffusion σ_z versus downwind distance from source for Pasquill's turbulence types.

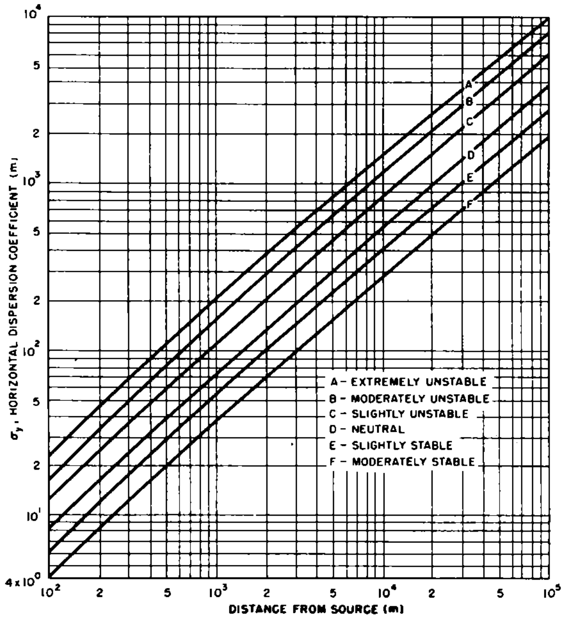


Figure 2. Lateral diffusion σ_y versus downwind distance from source for Pasquill's turbulence types.

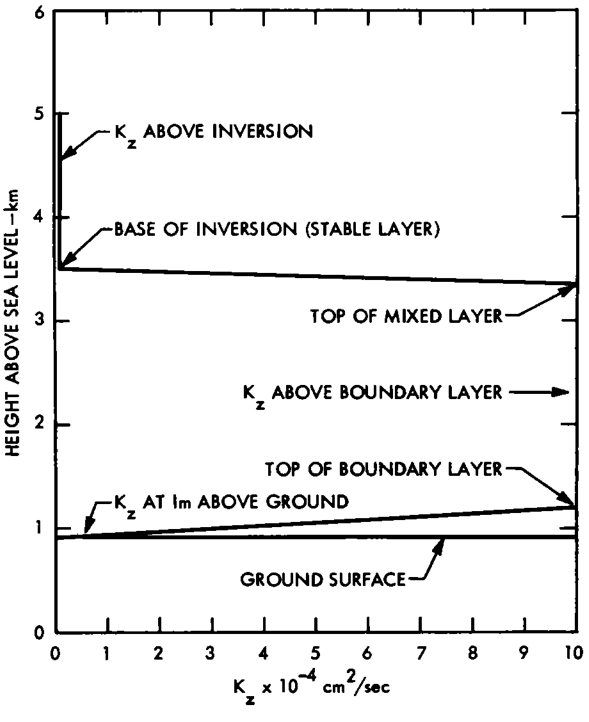


Figure 3. Model for vertical diffusivity as a function of height.

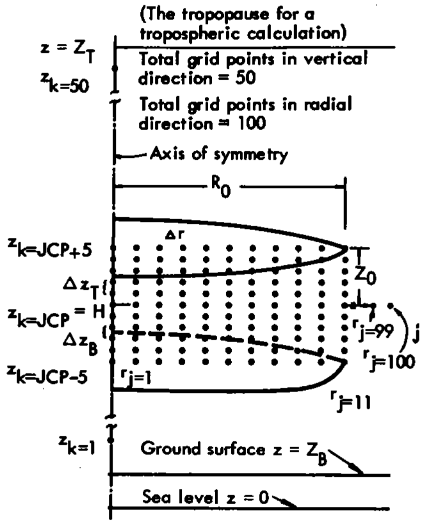


Figure 4. Grid system for the numerical diffusion model.

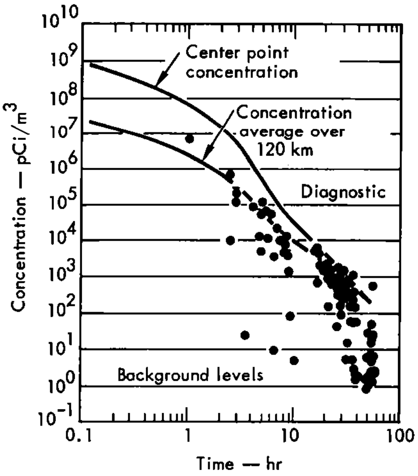


Figure 5. Calculated and measured airborne concentrations as a function of time for the NRX/EST EP-4A event of March 25, 1966.

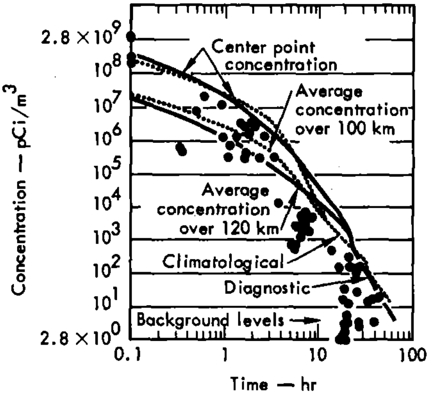


Figure 6. Calculated and measured airborne concentrations as a function of time for the Phoebus IB EP-IV event of February 23, 1967.

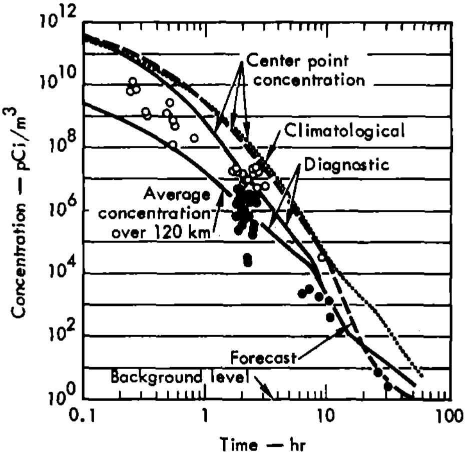


Figure 7. Calculated and measured airborne concentrations as a function of time for the Cabriolet event of January 26, 1967.

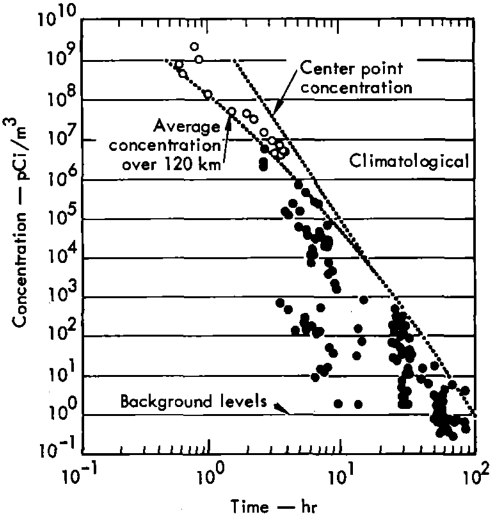


Figure 8. Calculated and measured airborne concentrations as a function of time for the Buggy event of March 12, 1968.

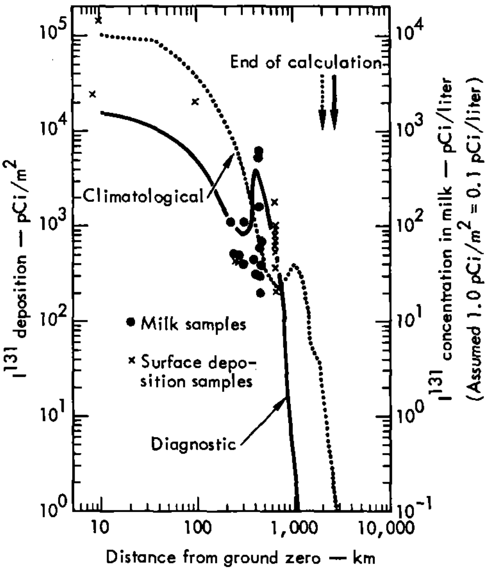


Figure 9. Calculated and measured iodine-131 deposition as a function of distance for the Cabriolet event of January 26, 1968.

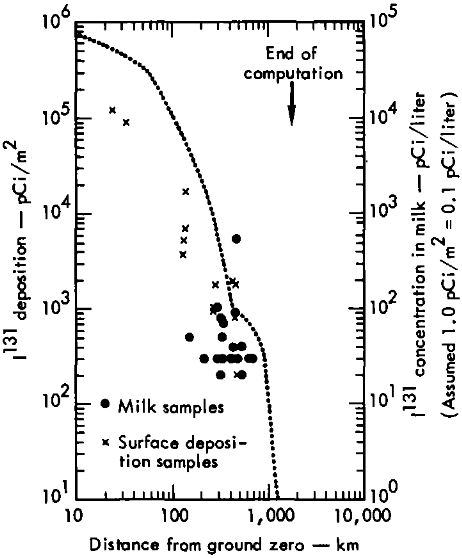


Figure 10. Calculated and measured Iodine-131 deposition as a function of distance for the Buggy event on March 12, 1968.

QUESTIONS FOR TODD CRAWFORD

1. From Alex Grendon:

Was it a slip of the tongue when you said that dilution was inversely proportional to wind speed and hence earlier arrival at a given point is accompanied by greater dilution?

ANSWER:

No, I'm not sure of the use of the term "inversely." If you look at concentrations as a function of distance downwind, it's got wind speed on the bottom of the denominator. So as wind speed goes up, concentration goes down. That's what I meant to say.

2. From Alex Grendon:

How would you interpret the horizontal line for the surface in the graph of K_z vs. height? It seems to imply that K_z near the ground is indeterminate.

ANSWER:

I'm not sure I completely understand the question, but the bottom curve on the graph I showed was a ground surface which was a horizontal line. Then I had a surface K_z coming back to some low value which I think on this particular example was 10^3. No, it is not zero at the ground and the values range at one meter from a few hundred centimeters squared per second at nighttime to a few thousand in daytime.

3. From Frank Baker:

Can you predict the effects of a heavy rainfall on the deposition of radioactive fallout? I am assuming that you purposely detonated an explosive to coincide with the rain.

ANSWER:

Well, the example I showed was a calculation for Cabriolet in a snow storm and this was in a factor of 2 accuracy. I am the first to admit that our understanding of all of the precipitation scavenging mechanisms and the mechanics of a good heavy thunderstorm are not very well known. But, I think we can make a good stab at it and calculate the effect of a detonation in a heavy storm.

4. From T. C. Rozzell:

In the four case studies presented for concentration of radioactivity as a function of time in the cloud, what radioactivity was measured--was it total or of one isotope such as iodine-131 used in the deposition study?

ANSWER:

The curves I showed for the four case studies were total activity.

5. From George Collins:

Are standard values of diffusion parameters such as those of Pasquill always used for predicting short-term micro-meso scale dispersion patterns, or are these parameters determined from on-site measurements where the detonation is to take place?

ANSWER:

There are two sides to that question. The discussion of Pasquill categories is related to the underground engineering, small gaseous leak kind of phenomena. That could be easily determined by a very general categorization of on-site weather and it would be used. The other question perhaps relates to the parameters used in the large cloud diffusion model which is not necessarily Pasquill's category. Those would also be determined from an examination of observed weather or forecast weather depending on the kind of forecast or what kind of calculation you were doing. Yes, on-site and near-cloud data are used.

6. From L. Anspaugh:

Your calculations evidently depend on an initial measurement of cloud concentration. How well can this initial value be predicted for a cratering shot?

ANSWER:

They don't depend so much on an initial value of concentration as they do on an initial estimate of total curies to put in the cloud. And the best way of answering that is to refer to the two Cabriolet and Buggy case studies I showed where the climatology, of course, had a calculation and pre-shot estimate of total curies, and post-shot calculations have actual measurements of total curies.

7. From William King:

Empirical values of σ_y and σ_z were obtained from observing particulate behavior. Do gases diffuse in a similar manner or do you use different values for predicting concentration of gases?

ANSWER:

In the context of my talk, we have been talking about both gases and particulate. If we have been talking about particulate, we have been talking about particles which are too small to act much like a particle--act more gas-like. So the answer to your question is that I used the words particulate and gaseous interchangeably, but with the assumption that the particles are too small to have any significant fall speed.

8. From C. A. Pelletier:

Apart from the health significance, clouds of radioactivity can be a nuisance to other nuclear operations by setting off stack monitors, contaminating low-level experiments, etc. Is it possible to give warning to these facilities in terms of estimated arrival time, and cloud concentrations?

ANSWER:

Yes.

9. From Darryl Randerson:

The presence of a cloud of radioactive debris is associated with an internal boundary condition, namely, a tight gradient of radioactivity. Finite-differencing schemes tend to "smooth-out" this discontinuity at a physically unrealistic rate. In your model, were you able to resolve this difficulty?

ANSWER:

A mutual concentration as a function of distance about the cloud center in my model is a gaussian one, and horizontally it's always gaussian. Numerical errors don't diffuse it faster, but horizontally it is always gassian. It's not gaussian vertically because the diffusion rates are a function of height according to that slide I showed and also your deposition seems to wipe out the bottom of the cloud.

SESSION III - PART B

Chairman: Mr. Ross L. Kinnaman
Nevada Operations Office
U. S. Atomic Energy Commission
Las Vegas

RADIOACTIVITY IN THE HYDROLOGIC ENVIRONMENT

Louis B. Werner
Isotopes, Inc.
Palo Alto, California

ABSTRACT

Certain proposed uses of nuclear explosives for peaceful purposes will introduce radioactive debris into the natural hydrologic environment. Consideration must therefore be given in each situation to the extent and significance to man of resulting radioactively contaminated water. For contained underground detonations, space-time-concentration predictions of radioactive materials in ground water are dependent on several factors: radionuclide production and initial distribution, radioactive decay, sorption on geologic materials, and dispersion during hydrologic transport. For uncontained (cratering) detonations, other aspects of the hydrologic cycle, particularly rainfall, and watershed characteristics must be considered.

Programs sponsored principally by the U. S. Atomic Energy Commission have investigated these factors. Examination of their net effects on radioactivity concentration in water shows that areas, if any, underlain by water exceeding permissible concentrations tend first to increase in size, then decrease, and finally disappear. Hydrologic processes at the surface remove or redistribute radioactive debris deposited on a watershed to other locations.

Where sufficient information is available, predictions of location and concentration of radionuclides in natural waters can be made. Any potentially hazardous conditions arising from a particular detonation can then be evaluated.

INTRODUCTION

Drinking water and food derived from contaminated hydrologic systems are potentially detrimental to man's health and welfare. Concern for possible human consumption of water contaminated with radioactivity dictates consideration of possible contamination of the hydrologic environment.

Radioactivity has always been present in water used by man. In fact, at times it has even been represented as beneficial. The prospect that harm is done by current consumption or use of naturally radioactive water appears doubtful in most instances. However there is no doubt that potential harm might result from uncontrolled releases of radiocontaminants from nuclear explosives, nuclear power generation, and industrial uses of radioactive materials.

The prospect for development of a major nuclear industry based on widespread use of nuclear explosives is at hand. Thus, it is quite appropriate to examine the Public Health Aspects of Peaceful Uses of Nuclear Explosives. Hydrologic contamination is relevant to this examination.

As we have heard, many types of nuclear explosive applications are under development. The presence of water in certain of these applications would be inconsistent with the objectives of the project. For example, construction of effective gas and petroleum underground storage capacity would be infeasible in active water-producing media. On the other hand, applications such as canal construction, or water resource development, inevitably would lead to contact of radioactive materials with natural waters. I should like to suggest that the significance of water contamination is not whether it may occur. Rather, the significance relates to: 1) extent of the water resource which is affected; and 2) steps which can or must be taken to preclude use of unacceptably contaminated water.

Prediction of extent of contamination of the hydrologic system by radioactive contaminants produced by an underground nuclear detonation requires analysis of the undisturbed hydrologic system. Prediction also requires knowledge of the relationship of the explosion zone to the hydrologic regime and characterization of radioactive contaminants in the explosion zone water.

Processes of sorption, dispersion, and radioactive decay which take place both in the explosion zone and in the hydrosphere outside the explosion zone must be considered. Because of unique combinations of nuclear devices, explosion application, and hydrologic system, each event-related evaluation of hydrologic safety tends to be unique.

Fortunately, the basic understanding of radioactivity in the hydrologic environment is relatively well advanced in large part through programs sponsored by the Atomic Energy Commission and its laboratories. Important contributions have been made by the Lawrence Radiation Laboratory, U. S. Geological Survey and others. Public safety and public assurance programs conducted in conjunction with the weapons testing program have been supported by the Nevada Operations Office (NVOO). Much that is applicable to peaceful uses of nuclear explosives has been learned in these studies. Non-testing nuclear programs have also made advances in hydrologic safety.

For the purposes of this paper however, I shall rely primarily on material developed under the hydrologic safety program of NVOO under Contract AT(29-2)-1229. I shall quote occasionally from NVO-40,(1) Technical Discussions of Off-site Safety Programs for Underground Detonations, and BMI 171-016, (2) Hydrologic Redistribution of Radionuclides around Nuclear Excavated Sea-Level Canals in Panama and Colombia. This study was supported in part under subcontract with Battelle Memorial Institute Management Contract for Radiological Safety Feasibility Inter-oceanic Canal Studies under AEC Contract AT(26-1)-171. For more detailed information reference to these reports is recommended.

I should like in this discussion to cover briefly the following points as they relate to predictions of hydrologic contamination:

1) The hydrologic environment and its relationship to explosion effects.

2) Interaction between radionuclides and water.

3) Hydrologic transport and prediction of space- time-concentration of radioactive contaminants.

4) Confidence levels in estimation of water contamination.

5) Surveillance of Water Quality.

6) Contamination Control.

7) Implications of water contamination.

THE HYDROLOGIC ENVIRONMENT

It may be well first to review briefly the nature of the hydrologic environment and specifically the hydrologic cycle. Figure 1 shows the essential elements of the hydrologic cycle. Precipitation as rain or snow ultimately either runs off into streams or lakes or infiltrates into the soil. Percolation to the water table (zone of saturation) results. Ground water flows in a direction dictated by hydraulic potential, i.e. from regions of higher hydrostatic to lower hydrostatic potential. Springs, lakes, rivers, plants and the ocean are replenished with fresh water. Water leaves the ocean, lakes and rivers by evaporation, and plants by transpiration.

A diagrammatic model containing essentially these same features is shown in Figure 2. Elements of precipitation, runoff, infiltration, recharge, groundwater flow, etc. are identified. An analogous diagrammatic model of radionuclide redistribution by water can be drawn as shown in Figure 3. This model indicates movement and storage of radionuclides.

Volatile constituents, for example tritiated water, will travel all paths of the hydrologic cycle. Soluble radionuclides move with the water except during evaporation but are retarded because of plant uptake and sorption on soil and rock particles. On the other hand, movement of particulate matter is largely restricted to surface water because of the filtering action of soil and rock.

Subsurface conditions assume particular importance because intimate contact between water and essentially all of the radioactive debris is possible.

The relationship of detonation effects to potentiometric surfaces is shown in Figure 4. Four detonation conditions are depicted schematically at varying scaled depths of burial corresponding to conditions of crater formation to complete containment.

If the potentiometric surface, or water table, is below all explosion effects the hydrologic contamination possibilities are minimal. They would be limited to recharge from surface water, downward infiltration and radionuclide transport through unsaturated medium. Contamination of ground water ultimately might result.

If the potentiometric surface is shallower but still beneath surface features, infill of rubble chimneys and crater fallback occurs. Where potentiometric surfaces are just below ground surface infill occurs. When an excavation or subsidence crater bottom is below the potentiometric surface a radioactive lake may form during readjustment of the potentiometric surface. If loss by evaporation is sufficiently low in relation to subsequent precipitation contaminated water will also flow into the ground water system from the crater in response to elevation of the hydrostatic level within the crater. Outflow could result if a crater or rubble chimney intersects confined aquifers which have hydraulic potentials above ground level. This corresponds to an artesian condition.

Fallout from cratering detonations is subject to leaching by rainwater. Contaminated water may infiltrate the groundwater system, run off the surface, or be subject to plant uptake. Ultimately, by either surface or subsurface transport radionuclides may enter lakes, streams and the ocean. Decreases in concentration of dissolved radionuclides will be caused by dilution, dispersion, decay and sorption. Reconcentration within the biosphere is a possibility.

Whenever a nuclear device is detonated below the potentiometric surface, the result is formation of a sink as shown in Figure 5. Ground water flow will be initially toward the sink until the potentiometric surface reaches equilibrium as shown in Figure 6. At this time outflow from the rubble in the explosion zone begins.

During outflow from the explosion zone, contaminated water adjacent to the downstream side of the explosion zone will immediately enter the hydrologic system. Contaminated water within the explosion zone will be subject to processes that will change the concentration of the contaminant with time, such as dissolution of radionuclides from explosion debris and sorption or desorption of radionuclides upon surfaces produced by the explosion. Uncontaminated water entering the upstream side of the explosion zone also will become contaminated as a result of desorption and dissolution of radionuclides from rock surfaces as it moves through the explosion zone.

Only simple examples of contamination of the hydrosphere by underground nuclear detonations have been discussed. It is probable that the section of rock intersected by the rubble chimney will consist of zones with varying hydraulic potentials and transmissivities. This hydrologic system, as modified by the nuclear detonation, will be complex. Interflow between aquifers, or outflow from craters might result. An analysis of the hydrologic system and of changes in the system caused by nuclear detonations is of utmost importance for predictions of hydrologic contamination.

WATER CONTAMINATION SOURCE TERM

Consideration will be given next to movement of the contaminated mass of water through the undisturbed hydrosphere. Transport equations have been developed which enable calculation of time- space- concentrations of radionuclides. Primary input for these equations is the water contamination source term. This source term is the initial concentration of radioactive contaminants in the explosion zone water where it is flowing out of the explosion zone. To provide the source term one requires the quantities of radionuclides produced initially and their spatial distribution in the explosion zone water.

The species and quantities of radionuclides are determined by device design and composition of the surrounding geologic emplacement medium and stemming materials. They can be estimated from knowledge of device design and performance.

Radioactive contaminants probably will not be distributed uniformly throughout the explosion zone. Actual concentration distributions have been measured in the field but too few data have been obtained as yet to produce a satisfactory theory. Present hydrologic contamination predictions assume conservatively that the radioactivity is evenly distributed through the explosion zone water, and that it is in water soluble form.

To complete the source term calculation it also is necessary to evaluate the effect of transporting the contaminated water out of the explosion zone.

Without going into a detailed discussion, it will be appreciated that such effects will be related to the character of the detonation and the hydrologic regime pertaining to each detonation.

For purposes of illustration let us consider contained detonations and return briefly later to consideration of some aspects of cratering detonations.

For the condition where flow is from the explosion zone into the ground water system the source term input to the transport equations will have a sharp front and a dispersed tail as shown in Figure 7. Dispersion, which relates to the distribution of velocities about the mean water velocity, in the explosion zone is responsible for this effect. The radionuclide transport equation requires a rectangular source term. The more complex but probably more realistic source term is approximated with a series of step functions.

The concentration of radionuclides in water in contact with rubble of course cannot be derived solely from solubility or consideration of solubility product constants of compounds in which they occur. Sorption of dissolved radionuclides on rock surfaces or sediments reduces concentrations to values below those derived from such determinations and retards the movement of the radionuclides relative to the water velocity.

Water in the explosion zone and in the aquifer is in contact with large surface areas on which sorption can occur.

The sorptive potential for various radionuclides on solid surfaces is determined by measuring the distribution coefficient (K_d) for the radionuclide. Rock and water from the zone of interest are used, if possible, in laboratory measurements of K_d. The distribution coefficient is defined as:

$$K_d = \frac{\text{Activity of the radionuclide in the solid}}{\text{Activity of the radionuclide in the water}} \times \frac{\text{Volume of water}}{\text{Mass of solid}}$$

For the range of rock-water combinations, distribution coefficients for radionuclides have been found to vary over two to three orders of magnitude. The distribution coefficient for a radionuclide is a quantitative index of the partitioning of the available quantity of that radionuclide between the solid and liquid phases of the system.

For example, a measured distribution coefficient of 100 would indicate that about 1/600 of the available element is in the water and the rest is sorbed on the rock surfaces. In a rock the ratio of volume of water to mass of solid is a function of the porosity.

TRANSPORT OF RADIOACTIVE CONTAMINANTS

Having defined the idealized source term-- the initial body of contaminated water-- we can examine its subsequent movement through the hydrologic system. This movement takes place of course in the down gradient direction. The rate of flow of water outside the rubble and fracture zone is that of the natural system. But, the rate of transport of radionuclides is less than the rate of flow of water. Sorption causes radionuclides, excepting possibly tritium, to be retarded relative to water.

The retardation of sorbed radionuclides is expressed by the following equation:

$$\text{Flow rate of Radionuclide} = \frac{\text{Flow Rate of Water}}{\text{Retardation Factor}}$$

The retardation factor B is

$$B = 1 + \frac{1 - \Theta}{\Theta} \rho \; K_d$$

where

Θ = fractional porosity

ρ = grain density of rock

K_d = radionuclide distribution coefficient

K_d was defined earlier as $\frac{As}{A_w} \times \frac{Vw}{M_s}$

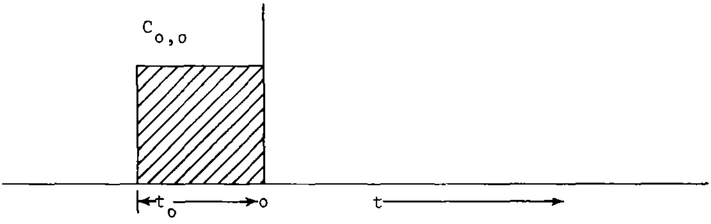
Since the retardation factor is dependent upon both porosity and K_d, the retardation factor theoretically can vary from one to infinity. In practice retardation may be great enough essentially to stop movement of the radionuclide. An interesting point is that if, for example, 99% of the radionuclide is sorbed it will travel at 1% of the average water velocity. That is, the bulk will travel at this rate. Some of the radionuclide will travel as fast as the water (theoretically). K_d and B merely make it possible to relate measurements on the same material in different physical states.

The redistribution of a radioactive contaminant can be described by a hydrodynamic transport equation as discussed by Fenske.(1) This equation, currently being used in the NVOO safety program, is an analytical solution in one dimension of the differential equation describing transport of contaminants through porous media. The two-dimensional distribution in a horizontal plane can be approximated by including an equation to estimate the effect of lateral dispersion.

Dispersion was defined earlier as the variation of water velocities about the mean velocity. Variations in mean velocities of water between streamlines through the aquifer as well as the explosion zone result in mixing of contaminated water with uncontaminated water, causing dissipation of sharp interfaces between contaminated and uncontaminated water during hydrodynamic transport. During the transport of contaminated water out of the explosion zone, the leading edge of the contaminant immediately enters the hydrologic system where, of course, it is subject to dispersion in the transport equation. The trailing edge of the contaminant slug, however, is also subject to dispersion resulting from transport within the explosion zone.

Because of the inherent stratification of most rocks, the large horizontal distances compared to vertical distances involved, and the desirability of considering outflow at different outflow points along the vertical dimension of the explosion zone, the vertical dimension is not considered in the transport program, but can readily be modeled by using the superposition of rectangular source terms as described earlier and shown in Figure 7. A large number of calculations are required to describe temporal-spatial variations of concentrations of the radioactive contaminant. To facilitate making the calculations, the transport equation has been programmed for a computer. The form of the transport equation defined by Fenske and Holly(3) is:

$$C(x,t)=\tfrac{1}{2}C_{o,o}\ \exp(-\lambda t)\left\{\operatorname{erfc}\frac{x-vt/B}{2\sqrt{Dt/B}}-\operatorname{erfc}\frac{x-v(t-t_o)/B}{2\sqrt{D\,(t-t_o)/B}}\right\}$$



Contaminant Transport Equation

Where

t = time measured from when the explosion zone outflows

t_o = the original length of the slug in terms of time of transit

x = distance from explosion point measured along a streamline

λ = radioactive decay constant of the radionuclide

v = the average seepage velocity of ground water

$B = 1 + \frac{1-\Theta}{\Theta}\rho\ K_d$ = retardation factor

Θ = porosity of the aquifer

K_d = distribution coefficient of the radionuclide between the solid and aqueous phase of the hydrologic system

D = dispersion coefficient

$C_{o,o}$ = initial concentration of radioactive contaminants

$\frac{Dt}{B}$ = one-half the variance of the radioactivity concentration curve

The equation describes the transport of a slug of contaminated water that was originally rectangular. The first term in the brackets represents the effect of transport on the front of the slug. The second term in the brackets represents the effect of transport on the rear of the slug. The exponential modifier preceding the bracketed expression corrects for radioactive decay.

The solution presented above is not a complete solution. Several terms have been neglected because the simplication obtained is great and the error caused by the neglect of these terms is small.

In most underground nuclear detonations the porosity and permeability of the explosion zone will be higher than the porosity and permeability of the surrounding undisturbed rock. As the contaminated volume of water flows into the ground water system it will occupy a larger volume of rock because of the smaller pore volume available and be lengthened in the longitudinal direction because of the higher ground water seepage velocity. The area underlain by contaminated water in the ground water system will be larger and of a different shape than the area underlain by contaminated water in the explosion zone. This effect is illustrated in Figure 8.

Output from the program is a series of matrices that can be converted into contour maps predicting the area distribution of radionuclide of interest with concentration isopleths. The present state-of-the-art does not permit the calculation of absolute concentrations with a high level of confidence. Ultimately a higher level of precision in concentration calculation should be possible. The probability is high, however, that calculated concentrations are equal to or above the actual concentrations. At the present time, instead of contouring concentrations, a line is drawn bounding the area which includes, with a high level of confidence, all concentrations above the maximum permissible concentration (MPC) for drinking water. Such a delineation is shown in Figure 8. Note expansion and contraction of areas underlain by concentration in water exceeding MPC. Similar contouring of concentrations up to 5xMPC have also been carried out.

Whether MPC or concentrations in water above or below this level are relevant is outside the exclusive purview of the nuclear hydrologist.

The objective of the nuclear hydrologist is to provide those physical data on water contamination from which an evaluation of potential hazard can be made. By AEC directive values in current use in the NVOO safety program are based upon concentrations given in USAEC Manual, Chapter 0524, Standards for Radiation Protection, Annex 1, Table II, Column 2, and reduced by a factor of three to be consistent with guidelines for uncontrolled areas.

Reference has been made to hydrologic effects in nuclear craters. Craters may serve as a direct route for transfer of radionuclides into ground water. The reverse condition may also obtain where ground water infiltrates into the crater carrying soluble radionuclides with it. For the condition of a cratering detonation it also is necessary that transport of dissolved or suspended fallout and crater ejecta be considered. This situation is more complex than that discussed earlier but is amenable to modeling and calculation. Consider the transport of contaminants dissolved by rainwater as developed by Charnell, Zorich and Holly.(2) As rainwater impinges on the soil surface, it contacts fallout radionuclides, some portion of which go into solution. Dissolved radionuclides are transported by runoff or soil infiltration. Infiltrating water does not enter ground water directly but is subject both to evaporation and to transpiration near the surface in the root layer. In some tropical areas of high rainfall, runoff normally occurs in a layer near the surface rather than over the surface. Percolation to ground water occurs under favorable conditions. The proportion of a radionuclide that travels either to a stream or to the ground water depends upon the rate at which the rainwater percolates below the surface layer. In general, rate of infiltration varies with time in a manner dependent upon precipitation history for the watershed. Following a dry period, infiltration rate is relatively high. The rate will decrease during a storm, due to alleviation of soil moisture deficiency, swelling of colloids, and compaction of the surface by raindrops. The total amount of dissolved radionuclide removed in runoff is determined by the ratio of runoff water to total water available.

The ground water system acts as a reservoir for water and dissolved radionuclides which are eventually discharged into streams. Migration of a radionuclide through the soil will be retarded relative to water due to sorption as discussed earlier.

As this brief description suggests, the complexities of the total hydrologic radionuclide transport system are very substantial.

Simplifying assumptions were necessary not only to reduce the problem to manageable size, but for correspondence between the degree of sophistication of the transport models and accuracy or availability of field data.

A summary of the equations which express quantities of radionuclide removed from the watershed in terms of the various hydrologic and physical variables and constants is shown in Figure 9.

Where

R = rainfall rate during the time interval Δt

I = infiltrated water

Q = runoff

ET = evapotranspiration

Q_{GW} = ground water flow

ΔNL = amount of radionuclide removed per unit area by leaching alone

F_w = fraction of radionuclide in the water $\left(\frac{1}{1 + \frac{1}{\alpha} K_d}\right)$

R_u = unit rain

N = amount of radionuclide on the soil surface

N_R = total quantity of radionuclide in the runoff for the time interval Δt

A = area of a watershed

N_I = amount of radionuclide in infiltration

N_G = amount of radionuclide in ground water

B_F = volume of base flow over the time interval

N_A = total radionuclide present in the reservoir

α = ground water reservoir porosity

H_r = effective thickness of the reservoir

This general model was applied by Charnell, et. al., to Route 17 in Eastern Panama. For this application it was necessary to divide watersheds into homogeneous subunits. Figure 10 shows for the fallout zone the sub-watersheds which were selected. Subdivision was accomplished by considering: 1) precipitation amount; 2) precipitation runoff interrelation; and 3) initial radionuclide deposition. Size of the areas near the canal alignment were kept somewhat smaller than those farther removed in view of the greater variation and concentration of fallout deposition in this region.

As an example, at a use point just down river from El Real, water is contributed from both the Chucanaque and Tuira Rivers. At that point, water and radionuclide would be contributed from sub-watersheds denoted as 6, 7, 8, 9, 11, 12, 13, 14 on Figure 10. Field information indicated that these sub-watersheds have similar geologic and hydrologic characteristics.

It was assumed that strontium in fallout might be distributed in an exponential manner away from the canal at completion of excavation. This was represented by one activity unit per square kilometer (A.U. km^{-2}) on sub-watersheds 6, 7, and 11, decreasing to 0.0001 A.U. km^{-2} on 14.

Following deposition, rainwater would leach strontium from the fallout and carry it downstream to the use point. A precipitation pattern was approximated by using the average quarterly rainfall rates. Some of the results of the calculations are the following:

> After one year, about 20% of the initially deposited strontium was calculated to have been removed from each sub-watershed surface by leaching and radioactive decay. Surface runoff would carry this material past the use point with a concentration, at the beginning of the year, of about 10^{-10} A.U. per liter. Near the end of the year the concentration of strontium-90 in the river water would decrease only by a factor of 2 to 0.5 x 10^{-10} A.U. per liter. During this same period, ground water would contribute strontium to the use point in a concentration that is nearly 4 orders of magnitude lower than that by surface runoff.
>
> A smaller distribution coefficient would cause a much higher concentration in the river water initially. Removal by leaching would be very effective and the concentration in river water would decrease rapidly. By extrapolation tritium with a very low distribution coefficient, would be removed from the surface almost entirely by the first rain. There would be a tritium surge in the river associated with this runoff but subsequent surface water runoff would contribute a negligible amount of tritium to the stream. After the first rain, the only device associated tritium in the river would come from the ground water. The annual contribution of tritium by ground water outflow from a watershed was calculated to equal about 10^{-3} of the total tritium deposited on the surface as fallout.

CONFIDENCE LEVELS

A necessary part of any estimate of contamination by nuclear explosion-produced radionuclides is an indication of the confidence that can be placed in the analysis. Field checking of hydrologic safety program predictions is costly and necessarily requires considerable time. The present hydrologic safety program therefore, lacks the field data necessary for confirmation of contamination estimates. For this reason, all expressions of confidence levels must be matters of scientific judgment. Although they are subjective, they possess useful validity.

The output from the NVOO-sponsored hydrologic safety program as discussed by Fenske,(1) is the temporal-spatial variation of concentration of the radioactive contaminant. Numbers specifying time, position, and concentration can have attached to them their standard deviation. This can be done by estimating the uncertainty of each factor contributing to the analysis and combining these variances in an error propagation equation to calculate the expected variance in the analysis. This confidence level, in other words, specifies the most probable value and the variation about this value that might be expected. Considering the state-of-the-art, these confidence levels are low. This technique not only determines the error in the analysis but also determines which component makes the largest contribution to the error and indicates where maximum improvement can be effected.

Alternatively, a statement of confidence can be made that the real concentration is equal to or less than the predicted concentration. Using the philosophy of selection of the credible but conservative input for all variables, upper limits on concentrations of radionuclides can be made with a high level of confidence.

Likewise, therefore, maximum exclusion areas can be stated with a high level of confidence. Much lower confidence levels must be associated with estimates of actual volume of the water resource degraded by a nuclear detonation. It may reasonably be expected that future studies will demonstrate that smaller volumes of water than presently stated are unacceptably contaminated, and that smaller sites or exclusion areas than presently used are acceptable for nuclear detonations.

It is very interesting to note that large (order of magnitude) errors in estimates of the absolute concentration of a radionuclide in the explosion zone water can be tolerated. Fenske illustrates this point with the following example for tritium:

> Assume the probable concentration of tritium in the explosion zone water is 1800 times MPC and the range of possible concentrations is from 400 times MPC to 3200 times MPC. The actual concentration not atypically might be expected to fall within this range 99.7% of the time. This water enters the hydrologic system. Although the upper limit of the range of possible concentrations is nearly an order of magnitude above the lower limit, the difference between the limits is equivalent to a decay time of only three half-lives. At ground water velocities of 60 meters per year, the contaminated volume will be transported about two kilometers farther before decay below MPC if the concentration is at the upper limit of the range than it is if at the lower limit. In such a case the range in location due to the possible range of concentration would be about 2 kilometers. At the one sigma level the error in location would be 370 meters. After several tens of years of transport this is a smaller error than that in an estimate of ground water velocity and direction.

SURVEILLANCE

The prediction of water contamination provides a basis on which to plan post-shot water utilization. However, once radioactive contamination has been introduced to the hydrologic system, surveillance is necessary to provide evidence of arrival or non-arrival of contaminants at a use point. Normally, appearance of water contaminated well below MPC would be of extreme interest in order that a monitoring program could be started and remedial measures initiated. The measured background radioactivity of natural waters varies considerably. This scatter of data can be attributed to errors in sampling, errors in analysis, and natural fluctuations within the hydrologic system. Assessment of the significance of data scatter by statistical methods is required where fluctuations in radioactivity of the sample are close to those of the natural system.

Dr. John Sharp,(4) Desert Research Institute, University of Nevada, has developed such statistical methods. Serial correlation, quality control and non-parametric techniques have been developed. These techniques are intended for recognition of uptrends associated with breakthroughs of explosion radioactivity which are superimposed on the pre-existing natural radioactivity of the water. Interpretation of analytical results has been aided by computerized statistical analysis techniques and development of a storage/retrieval system for monitoring data.

An adequate surveillance program involves collecting and analyzing enough pre-detonation samples to establish the natural background radioactivity of the water so that valid comparisons with post detonation water samples are possible. Satisfactory determinations of background radioactivity require the analysis of sequentially collected samples from each sampling point.

A post-detonation, sequential sampling program is needed to provide assurance on a long-term basis that contamination has not appeared at use points. If it has appeared at use points or monitoring points it may indicate the need for remedial measures or hydrologic controls.

HYDROLOGIC CONTROL OF WATER CONTAMINATION

Remedial or control measures may be instigated upon detection of breakthrough. They also may be applied at an earlier stage as part of a planned program of water utilization in the region of nuclear detonations.

As stated earlier, the rate and direction of flow of contaminated ground water is influenced by the character of the potentiometric surface. If this is known with sufficient accuracy it becomes possible to predict space-time-concentrations of contaminants, and plan water withdrawal so as to avoid the contaminated water body.

Techniques for hydrologic control have been employed for many years to control saltwater intrusion, flow of natural hydrocarbons, etc. Such techniques also are applicable to control of the movement of the body of contaminated water. One can for example, visualize pumping into injection wells outside the rubble chimney in such a way as to raise the potentiometric surface around the rubble chimney and temporarily immobilize the body of contaminated water. Similarly, it should be possible to divert, accelerate, or slow movement of contaminated water in order to optimize withdrawal and use of uncontaminated water. The use of aquifer grouting to reduce permeability selectively has been suggested but not evaluated. Whether these techniques can find application is largely an economic question. Certainly the most economic case is where contamination control can be exercised through accurate hydrologic analysis, a well designed monitoring program, and a corresponding water use plan which avoids the region through which contaminated water is passing. Typically, such passage might be complete within a few years. Dilution with uncontaminated water or water treatment could be considered. Other ameliorating approaches, where water contamination becomes a limiting factor may include optimization of yield, and device emplacement. By this means it may be possible to avoid water bearing zones, or involvement of hydrologic regimes which unnecessarily bring contaminated water to use points. In the case of cratering detonations techniques might be developed for minimizing release of radioactive debris to the surface environment. Since tritium appears to represent the greatest potential for off-site water contamination, selection of low fusion, high fission devices would be preferable in a hydrologic environment if other considerations are not controlling.

For some projects, a well designed monitoring system may provide all the protection required for public safety if planned in conjunction with remedial measures should these be found desirable.

IMPLICATIONS OF HYDROLOGIC CONTAMINATION

I would like to comment at this point on some additional implications of hydrologic contamination.

It has been noted that proposed commercial applications of nuclear explosives provide a broad range of possibilities for water contamination.

Techniques for prediction of space-time-concentrations have been developed and applied. Given applicable standards, acceptable sources of water can be delineated from unacceptable sources, and the extent of a natural resource, water, that must be withdrawn from human and animal use can be determined. Optimum water utilization programs can be designed or remedial hydrologic engineering projects undertaken. The analogy can be drawn with established practices for limiting releases of radioactive wastes into the environment from nuclear power plants, production plants, and other industrial activities. It should be possible to design nuclear explosive applications which would result in at least comparable safety features.

It is important to note a basic difference between prospective hazard from hydrologic contamination and some other hazards, at least insofar as use of water for domestic purposes is concerned. This difference is related to the time delay between detonation and potential exposure.

In general, the time between detonation and exposure to water contamination is much greater than obtains for seismic effects or airborne contamination. There is adequate time for analysis of water to determine whether unacceptable contamination exists. Also, there is time to instigate remedial measures or develop alternative water supplies. There is not the urgent need to drink contaminated water that there is to breathe possibly contaminated air. Inadvertent use of contaminated water can be prevented. It is difficult to conceive of applications where this is not so. Thus, the concern for water contamination can be translated into a consideration of economics rather than hazard. The question is what does it cost to buy safety? It can be bought at some price perhaps as a maximum, at the cost of an alternate, water supply for a number of years. Consideration has been given to risk-benefit aspects of applications of nuclear explosives. However, hydrologic safety is really a matter of cost-benefit. Cost-benefit calculations, of course, will be associated with uncertainties represented by the uncertainties of predicting the hydrologic contamination.

But, for any preselected criteria, the nuclear hydrologist can be expected to estimate the probable cost of insuring a safe water supply, and to place upper and lower limits on his estimates. By this means the economic feasibility of a nuclear detonation for peaceful uses can be assessed within the context of assured hydrologic safety.

REFERENCES

1. Fenske, P. R., *Technical Discussions of Offsite Safety Programs for Underground Nuclear Detonation.* Palo Alto Laboratories, Isotopes, a Teledyne Company, Palo Alto, California, U. S. AEC Report NVO-40.

2. Charnell, R. L., T. M. Zorich, and D. E. Holly, *Hydrologic Redistribution of Radionuclides Around Nuclear Excavated Sea-Level Canals in Panama and Colombia,* Palo Alto Laboratories, Isotopes, a Teledyne Company, Palo Alto, California. Battelle Memorial Institute, U. S. AEC Report BMI-171-016.

3. Holly, Donald E. and Paul R. Fenske (1966), *Transport of Dissolved Chemical Contaminants in Ground Water Systems.*

4. Sharp, J.V.A., In publication.

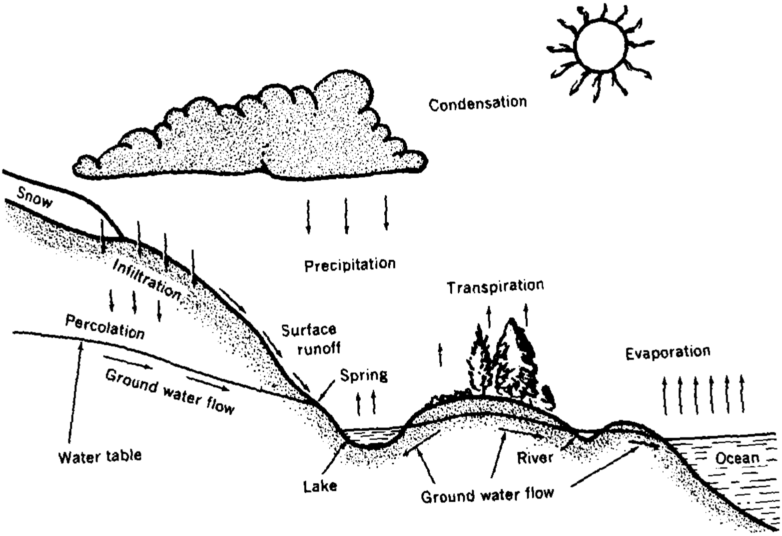


Figure 1. The hydrologic cycle.

David K. Todd, Ground Water Hydrology, Ch. 1, pg. 9

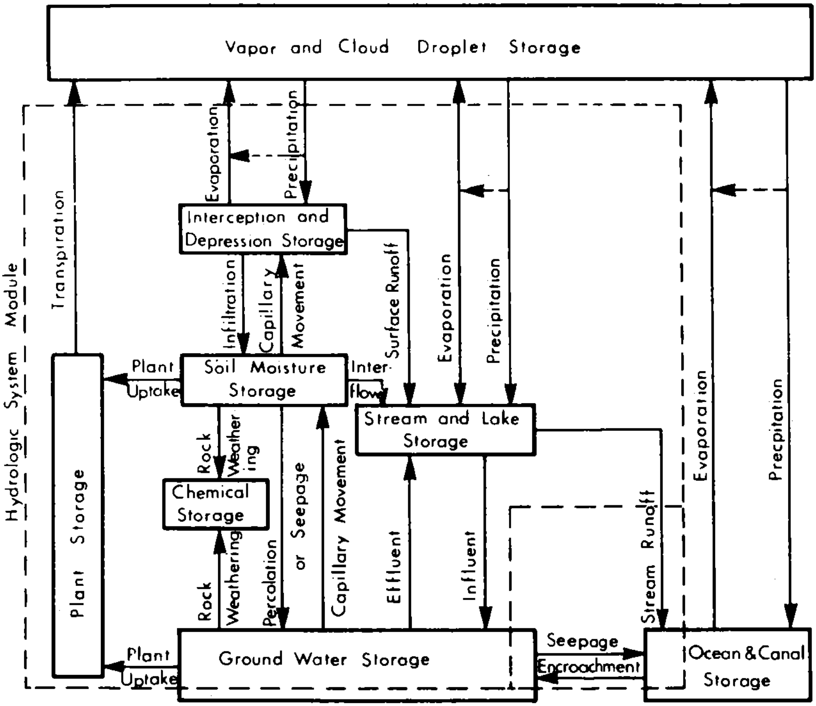


Figure 2. Diagrammatic Model of the Hydrologic Cycle.

P.R. Fenske and D. Sokol, Private Communication

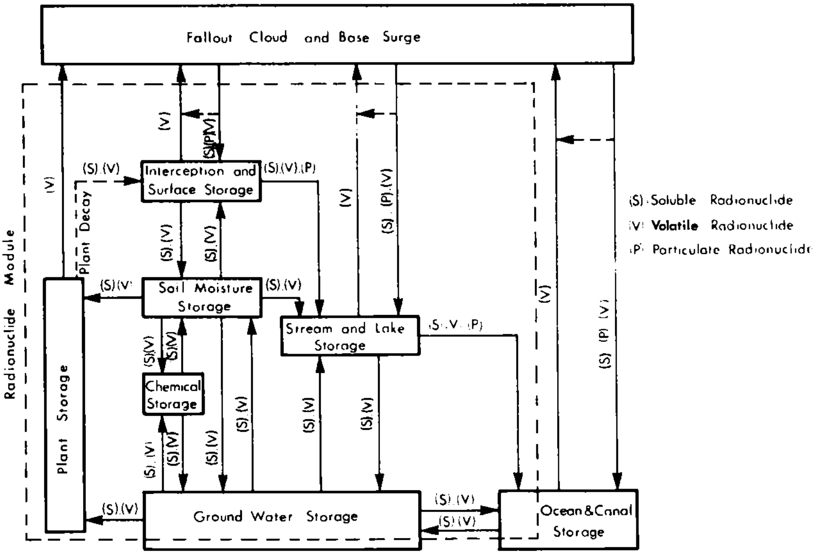


Figure 3. Diagrammatic Model of Radionuclide Transport By Water

P.R. Fenske and D. Sokol, Private Communication

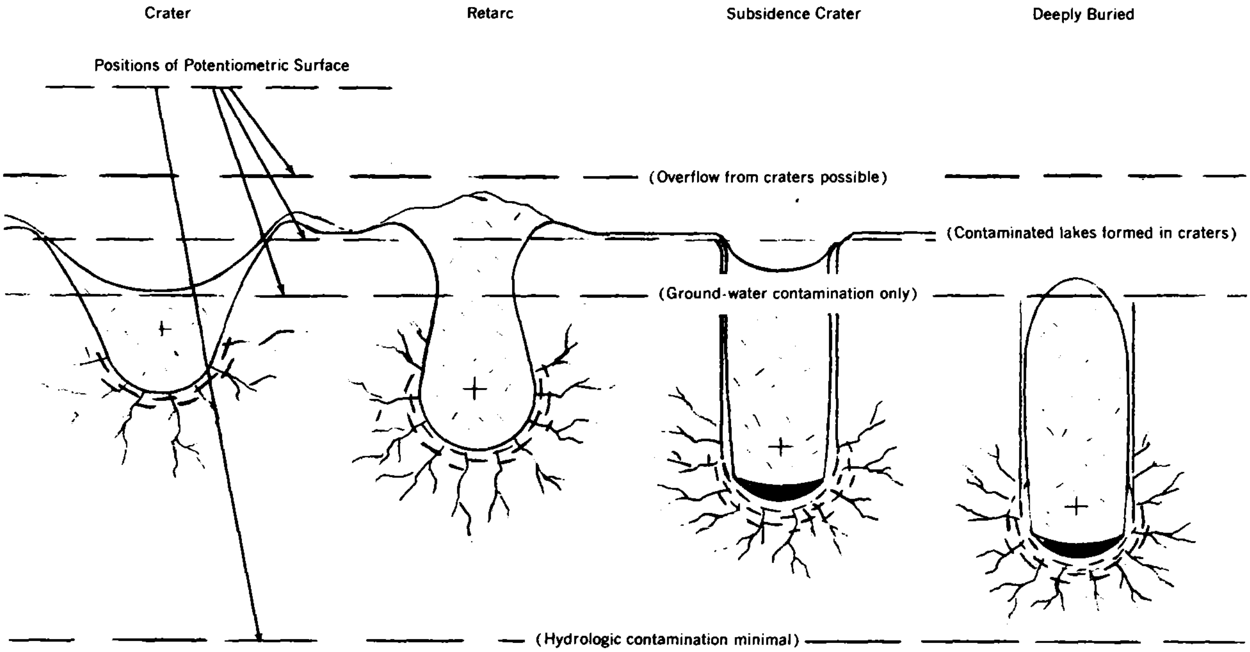


Figure 4. Relationship of Detonation Effects to Potentiometric Surface

P.R. Fenske, NVO-28(Revised) Chapter X, In Press.

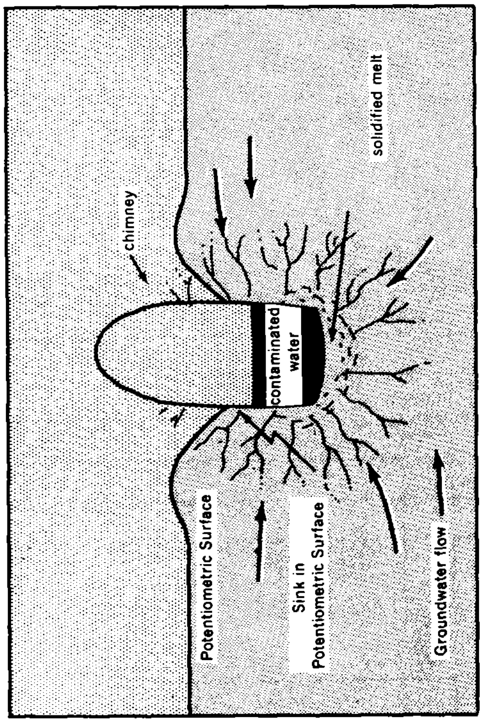


Figure 5. Readjustment of Potentiometric Surface
P.R. Fenske, NVO-40, Chapter 6

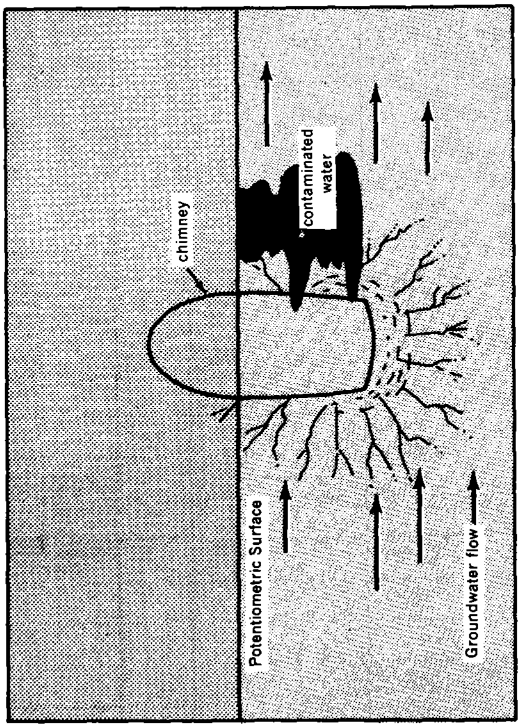


Figure 6. Outflow of Contaminated Water
P.R. Fenske, NVO-40, Chapter 6

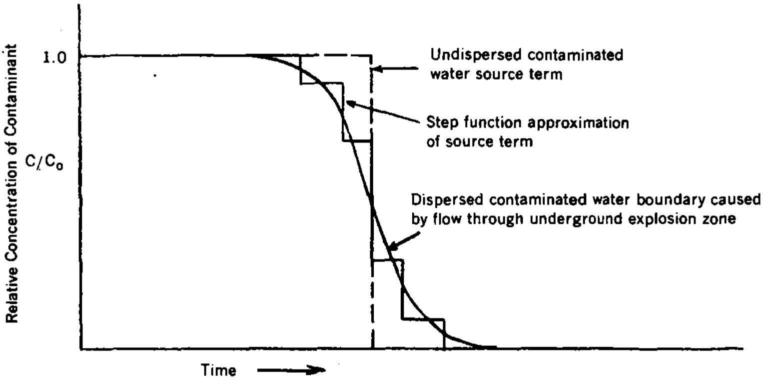
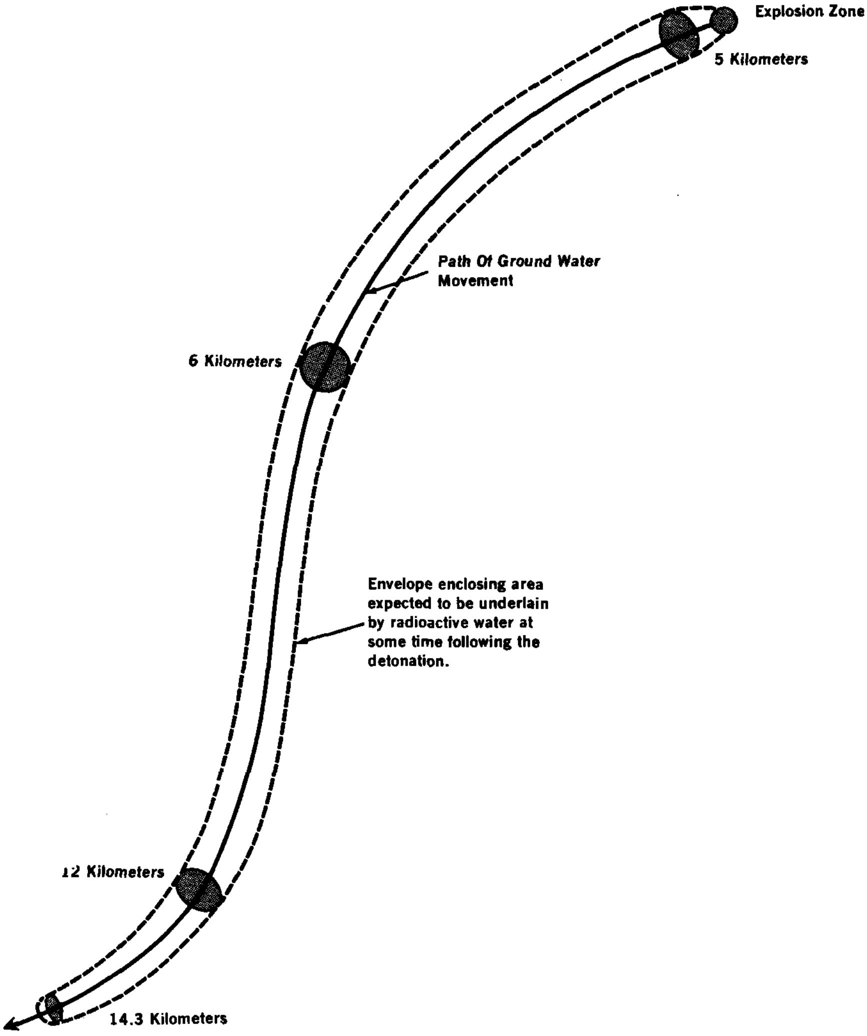


Figure 7. Source Term for Flow from Underground
Explosion Zone into Ground-Water System.
P.R. Fenske, NVO-40, Chapter 6



Total Migration distance 14.5 Kilometers (approximately 145 yrs.)

Figure 8. Hypothetical Contamination Prediction.
P.R. Fenske, NVO-40, Chapter 6.

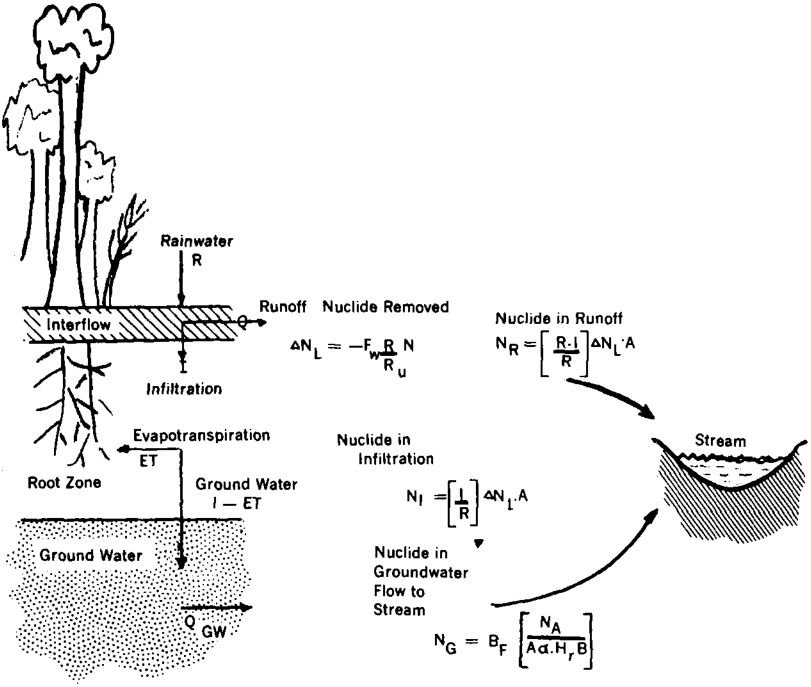


Figure 9. Schematic Diagram of the Fallout-Zone Redistribution
R.L. Charnell, et al., BMI - 171 -016

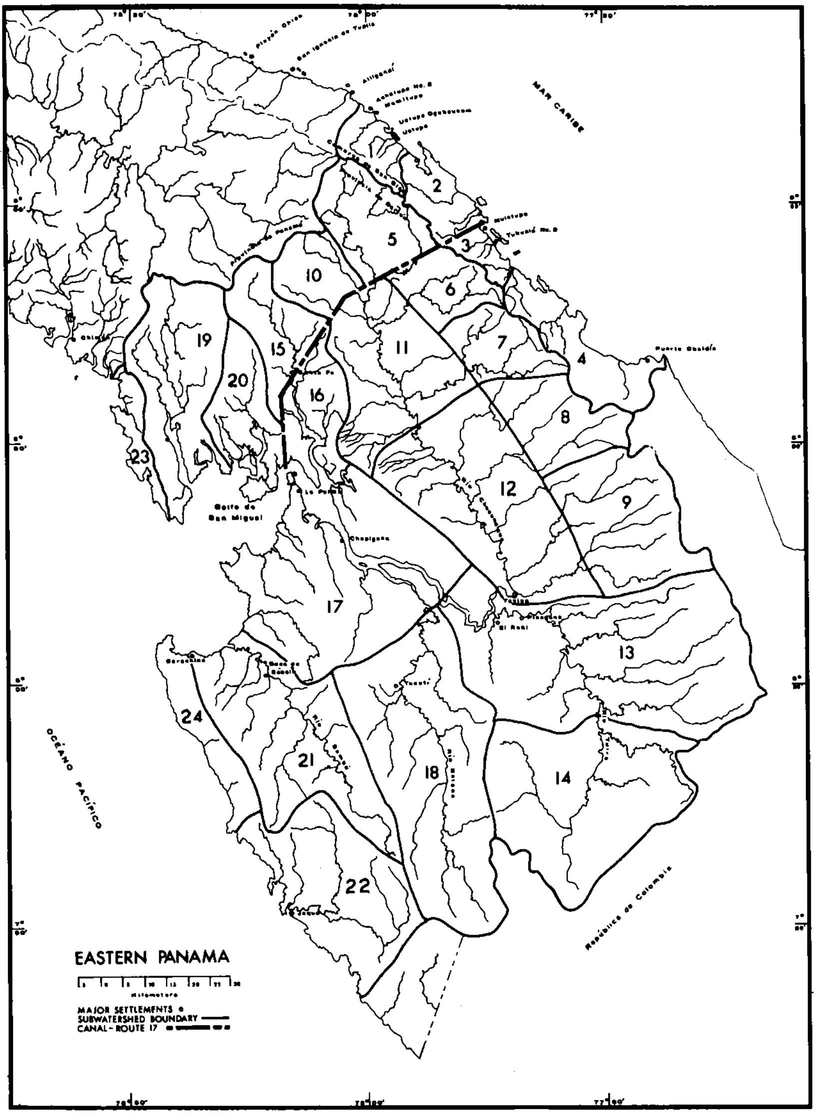


Figure 10. Delineation of Subwatersheds Around a Nuclear Excavated Sea-Level Canal in Eastern Panama.
R.L. Charnell, et al., BMI - 171 -016

QUESTIONS FOR LOUIS WERNER

1. From Dr. Lowman:

   Studies in Panama and Puerto Rico indicate that in a tropical rain forest sheet transport or sheet surface erosion is practically zero and most of the suspended river sediments are from channel erosion. What is your estimate on the reduction of the elution rate of tritium from the forest into the rivers as a result of this?

   ANSWER:

   Well, I'm not sure that there is going to be a good estimate of what this reduction will be by any means. This will be a part, I think, of the considerations coming out in the Battelle report and I am sure that this question is under consideration by the Battelle people who are responsible for it. For the study which was carried out by Charnell and others, it was necessary to make some simplifications which did not permit this factor to be evaluated, unfortunately. But, it does appear to be true that sheet erosion is not important. It appears to be true from what I hear from some of the people at Lawrence Radiation Laboratory that there is another mode of uptake of water which is directly by plants sort of a reverse of transpiration which is not an element of this model and so there will be certain adjustments that are going to have to be necessary.

2. From Alex Grendon:

   Was ρ omitted in the equation $K_f = \frac{1\text{-theta}}{\text{theta}} Kd + 1$?

   The legend defined ρ as density, but it does not appear here.

   ANSWER:

   The answer to that is yes, it was omitted. I discovered it when I was going over it in my notes and I did not call attention to it.

3. From Alex Grendon:

   Why was B used as a symbol for this same expression in a later slide?

   ANSWER:

   I think that is just the author's license. These were taken from two different investigators and one used one and one the other. I don't think there is any essential difference between them.

AIRBLAST FROM PLOWSHARE PROJECTS*

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ABSTRACT

The purpose of airblast predictions and monitoring is to guard against strong blast waves being carried by the atmospheric acoustic lens into populated areas where they could cause hazard and damage. Experience and theory, with both high explosives and nuclear tests, burst both underground and in the air, have been developed to allow reasonable confidence in safety predictions.

Standard explosion calculations and scaling laws are used to define the source strength to distances where quasi-acoustic propagation physics becomes valid. Underground bursts are attenuated by a factor which depends on scaled burst depth and the burst environment material. For row charges the source strength approaches a line source model with cylindrical blast expansion in directions perpendicular to the row.

Atmospheric refraction by strata of different temperatures and winds causes nonuniform blast overpressure patterns to be propagated great distances. Jet stream winds may duct and even focus airblasts with as large as 8X magnifications over standard wave expansion at ranges of 30 to 100 miles. Ozonosphere ducting, by warm temperatures and monsoon winds at 30 miles altitudes, can cause 3X magnification at ranges from 70 to 150 miles. For very large explosives, these atmospheric effects can cause nuisance damage and breakage to windows and plaster walls with a slight associated hazard to inhabitants.

Damage claims from explosive tests, accidents, and sonic booms have been analyzed to give damage prediction equations in terms of incident airblast overpressure and exposed population. Overpressures can be calculated from source strength and atmospheric propagation parameters. Measurements in communities

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*This work was supported by the United States Atomic Energy Commission.

surrounding various explosives tests have served to verify prediction procedures and interpret the validity of damage claims.

INTRODUCTION

Purpose

The purpose of airblast predictions and monitoring is to guard against strong airborne blast waves being carried into populated areas where they could cause hazard and damage. Our atmosphere, on occasion, acts like a lens for focusing blast or sound waves from explosions. This may cause much more airblast force at great distances than would be expected from safe distance criteria which are established for normal explosives in a nonrefracting atmosphere. Even relatively weak but audible compression waves, not usually considered to be of destructive force, may break some windows when applied to the large pane populations in a city. Large windows are most vulnerable to breakage and, in turn, create some significant hazard from falling and broken glass.

Plowshare explosives, burst underground, would give muffled airblast waves. The degree of muffling or attenuation for some conceivable events may not be enough to counteract all possibilities of atmospheric focusing. In planning, the yield, burst depth and material, and number of devices are used to establish airblast source strengths. Regional climatology for the particular site will allow seasonal estimates for propagation potentials, in terms of direction and distance. This allows identification of vulnerable communities and eventual damage cost and hazard evaluations.

If there is a problem, systematic blast prediction services may be required. This may entail special weather observations and forecasts, even to high altitudes reached only by rockets. Some blast prediction calculations require access to high speed computers. Where damaging airblasts are possible, they must be monitored so the measurements are available to verify predictions and to validate damage claims which may arise.

Background

Propagation of airblast to long ranges was regularly considered in the conduct of atmospheric nuclear tests. For Plowshare applications, however, underground emplacement of explosives causes considerable muffling of the airblast wave so that the resultant hazard to remote communities is much reduced. It cannot be ignored altogether, for many useful Plowshare explosives would use much greater yields than were allowed in continental atmospheric tests and the attenuation from burial is not great enough to completely suppress air wave formation.

Considerable data have been accumulated from cratering tests, where devices have been buried to give optimum crater sizes. Also, measurements have been made on a number of contained underground test events at various depths and yields. There is very little experience with burst depths of intermediate scale which might be applicable to quarrying or strip mining so expectations from these must, for the present, be interpolated.

On occasion, the atmosphere, with its stratifications of temperatures and winds, may act as a lens to converge and focus airblast waves at distances of fifty, a hundred, or even more miles. Near these foci, or caustics, ordinary acoustic amplitudes may be magnified by ten or more times and cancel the muffling effects of underground bursts where airblast is suppressed by attenuation factors of ten. Further definition of this attenuation is thus needed and is found to be dependent on yield, depth, and the environment material around the explosion.

PROBLEM DEFINITION

Explosion Blast Waves

Airburst explosives emit blast waves which are quite well understood; they are predictable by hydrodynamics and verifiable by measurement. Scaling laws are available for transforming airblast parameters from one yield to another, so that prediction starts with a standard explosion, here taken to be 1 kt NE (nuclear explosives) burst in free air with no reflecting surfaces and in a homogeneous, calm atmosphere at 1000 mb pressure (near sea level) and 300° K temperature (+27° C, 85° F). Complete tables of parameters for this explosion were calculated at Los Alamos and dubbed IBM Problem M. The pressure-time signature of this explosion wave at 9000 feet range, at the end of the calculation, is shown in Figure 1. This shows the typical explosion waveform with sharp compression, a slow decay into the long negative pressure phase, and gradual recovery to ambient pressure as the blast wave passes. The overpressure versus distance curve for this explosion is shown in Figure 2. Extension to smaller overpressures beyond the end of Problem M and below 0.37 psi was based on empirical data from high altitude bursts which were little affected by atmospheric refraction. In low overpressure regions, of concern to offsite safety, overpressure decreases in proportion to the 1.2 power of distance. Acoustic wave expansion would give a -1.0 slope but there are minor energy losses and waveform changes which cause the slightly more rapid decay which is observed.

Scaling laws are illustrated to show that a given shock strength, or overpressure-ambient pressure ratio, $\Delta p/p$, will reach to distances, R, which are proportional to the cube root of yield, W. Minor corrections for pressure altitude are included but for most Plowshares this can probably be neglected. Blast pressures at altitudes above sea level would be reduced and on the safe side. A target at 10,000 ft. above mean sea level (MSL) would receive about nine percent less than the graphed overpressure and at 20,000 ft. MSL the reduction would be 19 percent. Extra pressure scales are shown for millibars, metric units which have been in common blast prediction usage, and pst (pounds per square foot) which have been used recently in most sonic boom studies. Metric and mile distance scales are also shown for convenience.

The recorded, reflected overpressure at long range from an explosion is conveniently expressed by the equation

$$\Delta p^{*}\ \text{mb} = 714\ (\text{W kt NE})^{0.4}(\text{R kft})^{-1.2}(10^{-3} \times \text{p mb})^{0.6}\text{F} \qquad (1.)$$

where p is ambient pressure, Δp is blast overpressure, the asterisk indicates that the amplitude is doubled by ground reflection, W is explosive yield, R is distance, and F is the atmospheric focusing factor.

Underground Bursts

For underground bursts overpressures are reduced by muffling from the ground material. The wave form signature may also be changed, as shown by Figure 3, at various burst depths, where the initial shock transmitted through the ground strikes the air as a piston to give a "ground shock induced" (GSI) pulse which is followed by a "gas vent" (GV) pulse if there is cratering or venting. At shallow burst depths only the GV pulse is observed, at optimum crater depths in alluvium the two pulses are observed, and at contained depths only the GSI pulse gets into the air.

Amplitude is described by a transmission factor, T, defined as the ratio of overpressure emitted to long range divided by the overpressure which would have resulted from the same explosive, but burst in free air, or

$$T = \frac{\Delta p\ (\text{W, underground burst})}{\Delta p\ (\text{W, airburst})} \qquad (2.)$$

Transmissivity at close range is much complicated by several factors and a full physical description of what takes place is not yet available. Only the distant observed values will be considered here in relation to offsite safety. Smoothed curves through experimental data are shown versus scaled (according to $W^{1/3}$) burst depth in Figure 4. There is much scatter, partly caused by non-uniform emissions from the source and partly from atmospheric inhomogeneity over the long transmission paths. For safety predictions some allowance must be made for this possibility of error. Curves show that the material environment of the burst may be quite important. Nuclear bursts in moist materials generate a large steam pressure which enhances the GV amplitude. Bursts in dry rock at optimum cratering depths have only a small venting pulse pressure and the GSI pulse is the maximum of the two.

Contained underground bursts under alluvium are much attenuated in comparison with stronger waves emitted by bursts under rock; bursts in salt formations have appeared to give the greatest air wave outputs.

Overpressures in Figure 1 are multiplied by the appropriate transmissivities from Figure 4, to give overpressure-distance curves for various explosives applications. Some examples are shown in Figure 5. These are "Standard" propagation curves for hemispherical propagation from these bursts, to be multiplied by appropriate focus factors for specific atmospheric refracting conditions.

If multiple charges are detonated simultaneously the blast waves may add almost acoustically and cause greater overpressures than would have occurred from a single burst of the combined yield. This may be alleviated by firing at time intervals but the excavation efficiency may then drop enough to make this impractical or undesirable. Data have only been obtained for the simultaneous detonations of rows for ditch digging. Maximum airblast amplitudes are propagated perpendicular to rows and the minima are emitted off row ends. A multiplier for number of charges is shown by Figure 6 for these two directions and intermediate directions may be interpolated. Row charge effects are not yet well understood so tests and studies are continuing on this problem. Total error from transmissivity, row charge effect, and atmospheric variability may be by a factor of three or four.

Atmospheric Propagation

Atmospheric refraction causes non-uniform blast pressure patterns to be propagated great distances. A simplified illustration of this is shown in Figure 7. In a real atmosphere temperature changes with altitude, as shown by the left curve, so that sound speed is also different at different altitudes. Wind changes with height added to temperature-determined sound speeds give a sound velocity versus height structure, as shown by the dashed curve. A vertical plane wave, as shown on the right, would be propagated through this atmosphere at different velocities at different altitudes and become increasingly distorted with passage of time. Sound rays, perpendicular to the wave front, are curved upward away from ground in layers where sound velocity decreases with height. These sound rays are curved toward the ground in layers where velocity increases with height.

This same bending affects rays from a point source or explosion, as shown in Figure 8. A most important sound velocity versus height structure for explosions is where sound velocity decreases, then increases with height above ground. Various rays emanating from a burst curve upward, then are turned over by velocities aloft and return to ground in a band some distance away. Relative blast intensities may be predicted from the density of ray arrivals. There may be varying degrees of focusing of blast waves in these sound rings. This is usually the sound velocity versus altitude profile which causes exceptional disturbances, sometimes called caustics, at long ranges.

There are three layered regions of the atmosphere which may give strong sound or blast propagation. The lowest, a surface inversion layer, as shown in Figure 9, does not often give significant focusing but instead causes wave energy to diverge cylindrically rather than spherically, and thus causes abnormally high blast pressures. This surface sound duct may be generated by a surface temperature inversion, where temperature increases with height above ground in a shallow layer which is seldom more than 1000 feet thick. Inversions develop at night when the ground cools by radiation and, then in turn, it cools the boundary air layers by conduction.

With temperature decreasing with height, as is normal in daytime when the ground is heated by the sun, wind direction or speed may change with height to cause a sound velocity inversion. In either case, sound rays are ducted to strike first at ranges of less than a couple miles. These sound rays are almost perfectly reflected by the ground (at least for frequencies and wave lengths given by most explosions) and repeat their cyclic path many times as illustrated. Even small ground reflection losses become significant after being compounded dozens of times so this atmospheric duct is only of concern in blast prediction to a few tens of miles. In Nevada this shallow duct is generally blocked by mountains at less than 20 miles range.

Weather conditions shown in Figure 10 are responsible for past occasions of extensive blast damages at exceptional distances. Jet-stream winds, which usually blow from the west direction quadrant, may have speeds as high as 250 knots. Very low temperatures and sound speeds at 25,000 to 40,000 feet are counteracted by these high wind speeds to give some higher sound velocities toward downwind directions near tropopause altitudes than at ground level. The tropopause is where temperature stops decreasing with altitude. A resulting sound ring, with possible strong focusing, may land at 30 to 100 miles downwind range, depending on height and strength of ducting jet-stream winds.

At higher altitudes, as shown by Figure 11, in the ozonosphere there is a warm layer centered near 150,000 feet, where temperatures and sound speeds are nearly as high as at ground level. Fairly steady, strong winds to 150 knots speed blow with seasonal directions at these high altitudes, from west in winter and from east in summer. This creates sound ducting toward downwind directions which gives a sound ring at ranges from about 70 to 150 miles.

Upwind, blast waves are refracted away from ground and only minor waves are diffracted or scattered into the shadow zone, while stronger blast waves pass far overhead. These diffracted waves have sometimes measurable but usually inaudible intensity, and about two percent of the downwind pressure amplitude.

Even higher, in the ionosphere above 300,000 feet, very high temperatures also duct waves to strike the ground at over 100 mile distances. This ducting is usually carried in directions opposite from downwind ozonosphere propagation. At such high altitudes, low air densities cause most blast wave energy to be absorbed, so no structural damages have been reported from this wave route. However, high frequency pops and rattles have been observed when ionosphere waves from large explosions do reach the ground.

At long range waves strike ground at incidence angles of up to 30 degrees and their amplitudes are doubled by near perfect ground reflection. Microbarograph recordings thus show twice the free air incident values calculated by scaling from Figure 2. This doubling is sometimes incorporated into expressions for the effective focus factor, although the ray convergence by atmospheric refraction only contributes half of total recorded focusing.

Airblast magnification by atmospheric ducting and focusing is defined by a focus factor, F, which is the ratio of observed or calculated amplitude or overpressure to that which is obtained from standard explosion propagation or

$$F = \frac{\Delta p \text{ (W; real atmosphere)}}{\Delta p \text{ (W; homogeneous, calm atmosphere)}}$$

Propagation under a surface inversion may give ducted focus factors of F = 2 or F = 3, as shown by recordings made 10 to 20 miles from nuclear tests in Nevada. Mountainous terrain in Nevada interferes with this propagation so there have been no opportunities to observe results from this ducting to longer distances. Even at ten miles range, atmospheric inversions may cause an explosive to sound like ten times its actual yield. In effect the explosion wave is nearly limited to cylindrical rather than spherical divergence.

Jet stream ducting may cause much larger blast magnification. Experiments have shown 1.6X magnification is about average within 10 miles of an expected caustic, F = 4.2 has been observed, and statistical extrapolation shows that 7.5X may well hit some houses or buildings from some explosive events. This ducting is usually toward eastern directions, because jet stream winds usually have large west wind components. Occurrence is generally limited to late fall through early spring seasons and temperate latitudes.

Ozonosphere propagations also give common observations of 1.5X magnification. The largest recorded value showed F = 3.3 at 135 miles from a 15-ton HE (high explosive) event.

Uncertainty about the atmosphere over such long paths makes predictions subject to considerable error. The changing nature of our atmosphere makes duplication of propagation difficult, even over time intervals of a few minutes. Prediction error factors of at least two, high or low, should be allowed. More realistic assessment for damage expectation requires consideration of the whole statistical pattern of probabilities so that serious impacts can be held to rare occurrences.

Effects from Small Amplitude Airblast Waves

Laboratory tests have not broken panes with less than 10-mb overpressures, but the number of panes tested nowhere approached the number of panes exposed even in small cities.

A more realistic damage level threshold for nuclear test waves on cities can be estimated from three incidents of large, single-strength, aged glass panes breaking from 2-millibar recorded overpressure (1-mb incident). At higher overpressures there were quite a few moderate size panes broken in Johnston Island barracks by Orange shot which gave 14 mb recorded overpressure. At the Nevada Test Site, 17 millibar overpressure is the maximum recorded at the CP-1 Control Point in Yucca Pass, but that tore doors loose and broke ceiling light fixtures. There have been several other claims of damage from testwaves, but there were no associated pressure measurements.

Better laboratory data are needed to relate breakage probability to overpressure. This may come from sonic boom and supersonic transport studies. Meanwhile empirical results from the Medina, Texas, accidental explosion incident of November 1963, furnish a useful guide to relating breakage probability to overpressure, glass pane size, etc. Of 12 million panes exposed in San Antonio, 3644 were claimed broken, by overpressures estimated to vary from 1 mb to possible 10 mb, from destruction of 115-tons of chemical explosives.

It was found that there were about 19 times as many window panes in San Antonio as there were people, and that the average window repair cost was $15.80. A small number of very large panes was very costly to replace. In summary, as shown by Figure 12 for a typical city of 100,000 population, the number of expected broken panes can be estimated in terms of expected overpressures. This estimation method was applied to a ranch house where one pane was broken by an explosive test near Cedar City, Utah, in October 1968, and showed that only 0.47 pane should have broken.

It has also been found, and sonic boom tests are in substantial agreement, that miscellaneous damages, cracked plaster, broken bric-a-brac, and so on, may increase damage claims costs by about 40 percent over the cost for windows alone. Engineering details on structural responses of these miscellaneous types are practically impossible to obtain.

Purely economic considerations of airblast restraints on Plowshare events must be tempered by possibilities for personal injury. There would be no direct physiological damage to people with less than about 5 psi overpressures, or 350 mb where eardrums may break. One psi may cause injury from falls or other reactions to startle or airblast force. At much lower pressures secondary hazards from broken or breaking glass must be considered outside the cost-effectiveness approach. Fortunately there is practically no solid information available. No one was hurt by broken glass from NTS nuclear tests nor in the Medina incident. There were, however, fifteen injuries reported from 300 broken panes caused by a recent sonic boom at the USAF Academy. It is hoped that the detailed Air Force report on this incident will assist in evaluating the hazard potential of breaking windows.

SUMMARY

Blast predictions begin with a hydrodynamic definition of the close-in source wave which is well-known in terms of yield, explosive and other scalable factors. Plowshare excavation events are muffled or attenuated in varying degrees according to scaled burst depth and material environment, and experiments are continuing to adequately define this.

Once an airblast wave is coupled into the atmosphere, long range propagation depends on the vertical structure of temperatures and winds, sometimes to great altitudes. Sound ducting by refraction processes can be caused by the boundary layer, by jet stream winds, by seasonal winds near 150,000 feet altitude, and by high temperatures in the ionosphere above 300,000 feet. Airblast amplitudes can be calculated for these atmospheric lens effects at long ranges. There is confidence in the qualitative results but there are frequent factor-of-two errors which must be guarded against in assuring safety.

Theories are inadequate and data are scarce for predicting nuisance damages from small amplitude waves. Research is continuing to refine this sector of the airblast problem as needed for Plowshare safety and feasibility studies as well as supersonic transport sonic boom problems.

REFERENCES REGARDING VARIOUS PHASES OF PLOWSHARE BLAST PREDICTIONS

1. Cox, E.F., H.J. Plagge, and J.W. Reed, "Meteorology Directs Where Blast Will Strike", *Bull. Amer. Meteor. Soc.*, Vol. 35, No. 3; pp.95-103, March 1954

2. Cox, E.F., "Sound Propagation in Air", *Handbuch der Phycik*, Vol. 48, Chapt. 22, Springer-Verlag, Berlin, 1958

3. Broyles, C.D., "IBM Problem M Curves", Sandia Corporation Technical Memorandum SCTM-268-56(51), December 1956

4. Reed, J.W. and H.W. Church, "Sedan Long-Range Blast Propagation", Plowshare Program Report PNE-202F, August 30, 1963

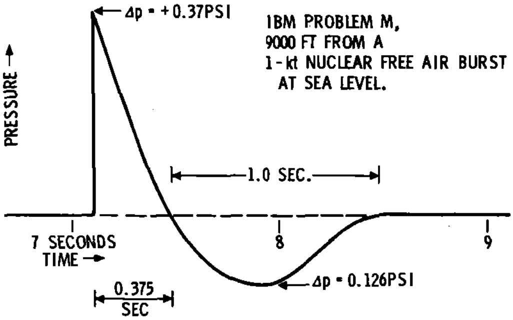
5. Reed, J.W., "Long-Range Air Blast Measurements and Interpretations", Project Dannyboy Report POR(WT) 1809-1, August 1963

6. Reed, J.W., "Long-Range Airblast", Operation Sailor Hat Report POR-4057, (WT 4057), August 2, 1966

7. Reed, J.W., "Multiple Row Charge Blast Wave Observations at Long Range", Project Dugout, Plowshare Program Report PNE-607F, Spetember 8, 1966

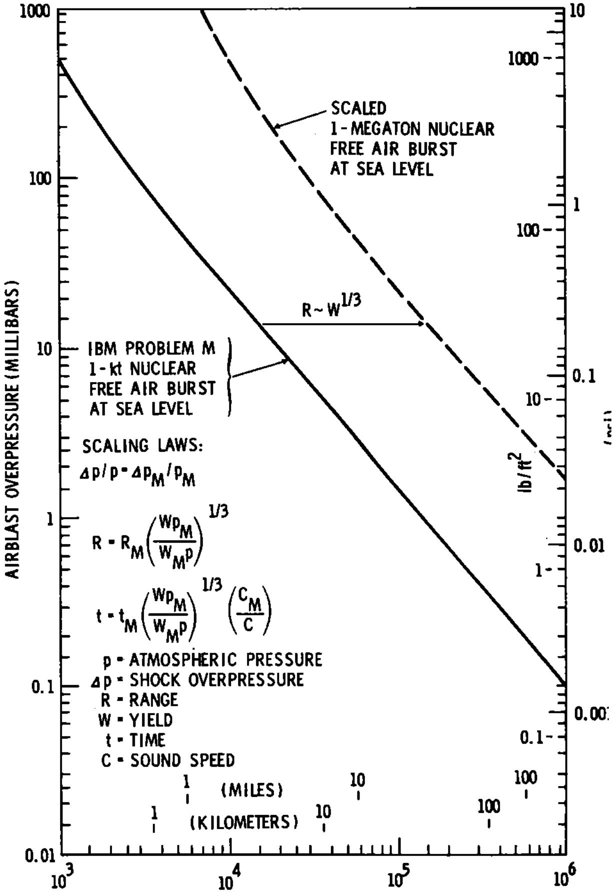
8. Reed, J.W., and C.J. Vortman, "Air-Blast Measurements - Project Pre-Schooner II", Plowshare Program Report PNE-512F, February, 1968

9. Reed, J.W., "Long Range Airblast - Project Palanquin", Plowshare Program Report PNE-903F, July, 1967



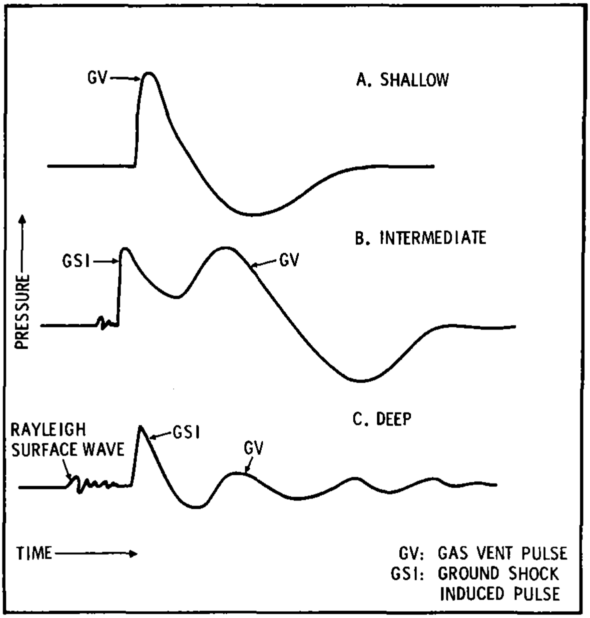
EXPLOSION WAVE PRESSURE-TIME SIGNATURE

FIGURE 1



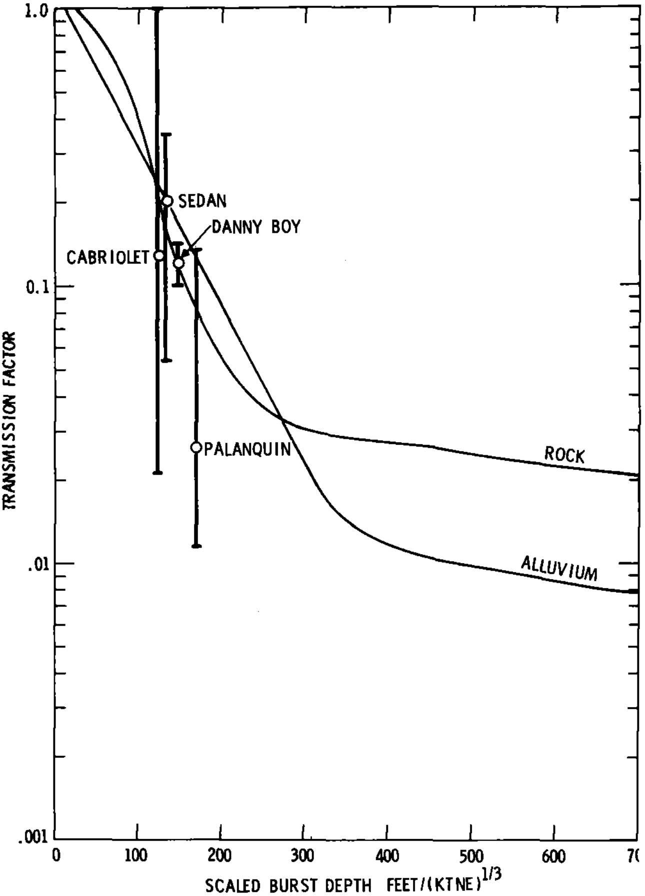
STANDARD EXPLOSIVE OVERPRESSURE-DISTANCE CURVES

FIGURE 2



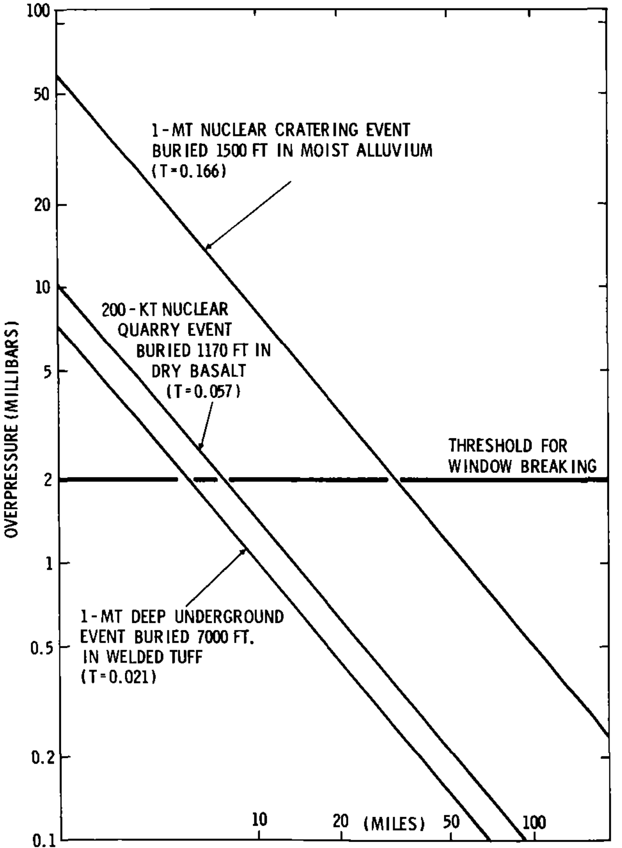
CRATERING EXPLOSION PRESSURE-TIME SIGNATURES.

FIGURE 3



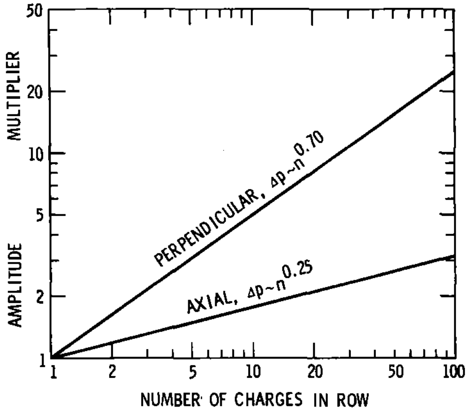
TRANSMISSIVITY FROM UNDERGROUND BURSTS

FIGURE 4



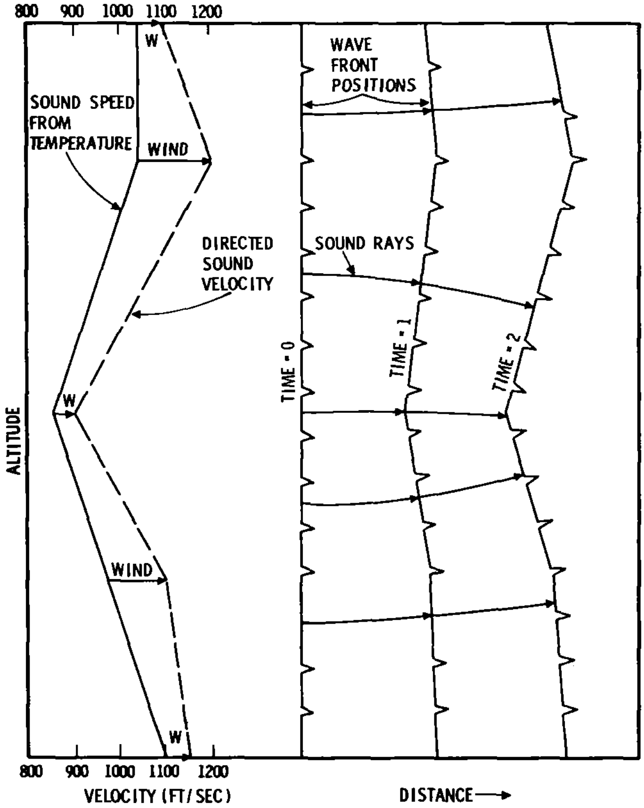
EXAMPLES OF STANDARD PROPAGATIONS FROM BURIED EXPLOSIONS.

FIGURE 5



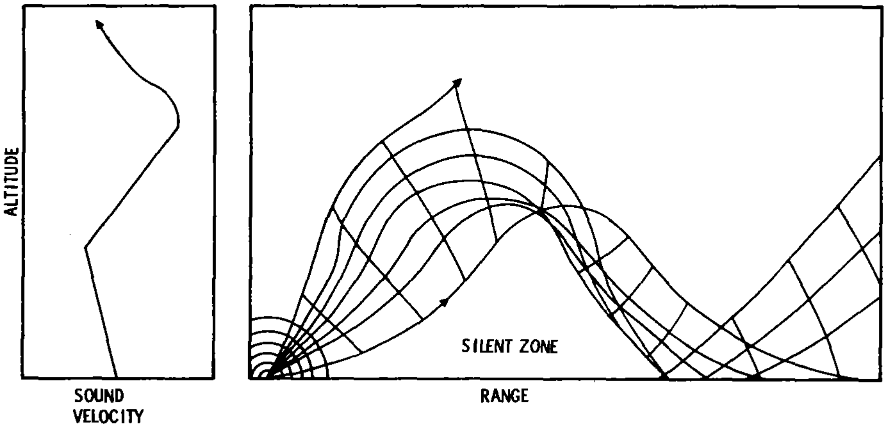
ROW CHARGE EFFECTS, PERPENDICULAR AND AXIAL DIRECTIONS.

FIGURE 6



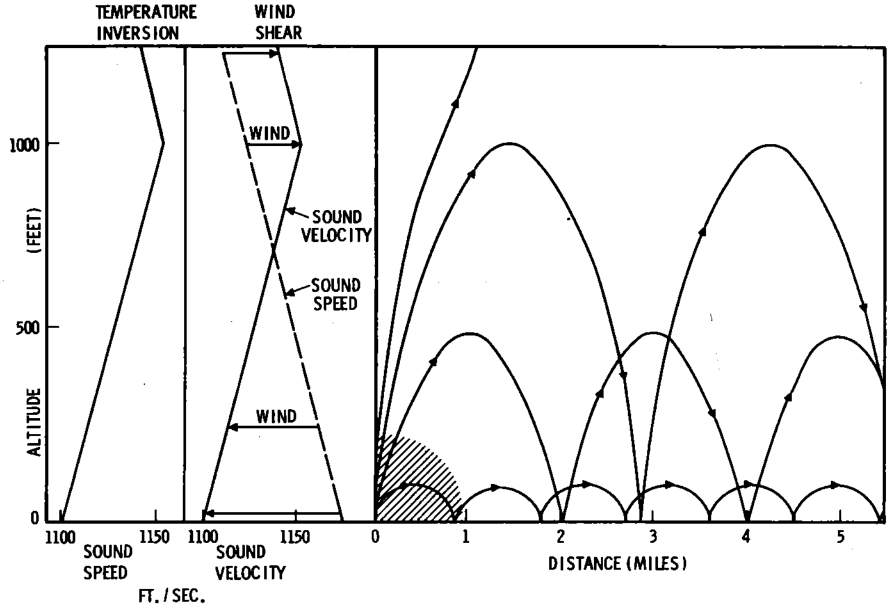
SHOCK-WAVE DISTORTION BY LAYERED ATMOSPHERIC TEMPERATURE AND WIND STRUCTURE.

FIGURE 7



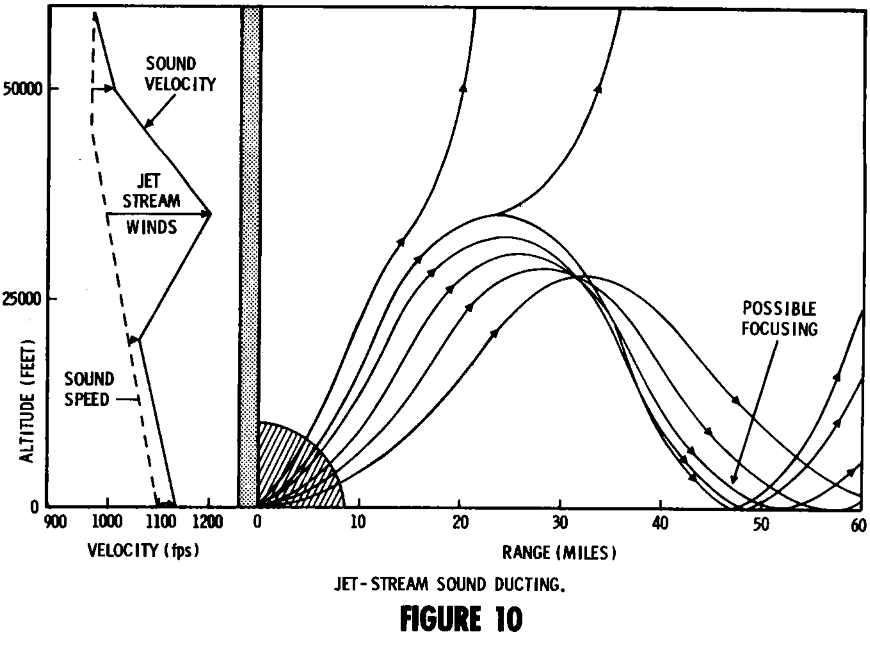
TYPICAL EXPLOSION RAY PATHS

FIGURE 8



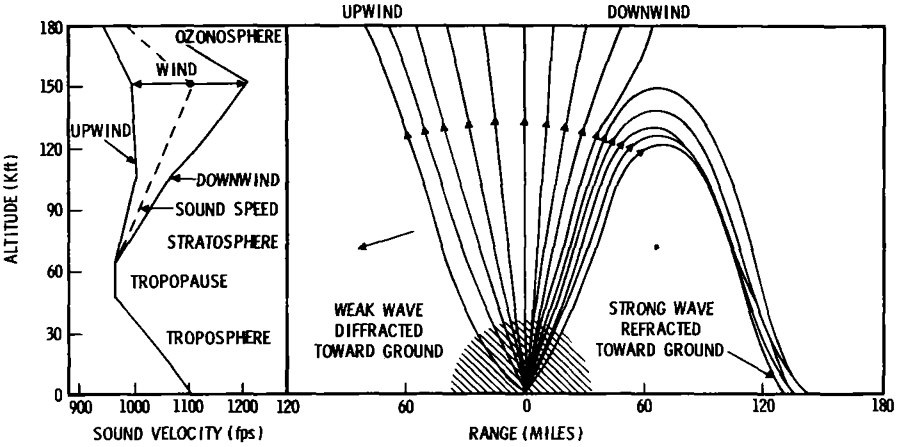
SURFACE INVERSION SOUND DUCTING.

FIGURE 9



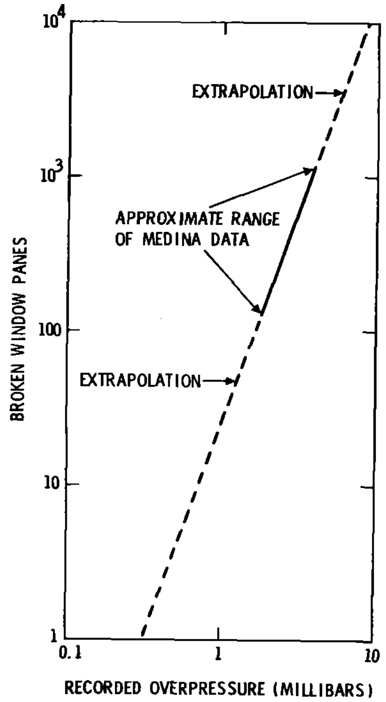
JET-STREAM SOUND DUCTING.

FIGURE 10



OZONOSPHERE WIND EFFECT ON SOUND DUCTING.

FIGURE 11



EXPECTED WINDOW DAMAGE VERSUS EXPLOSION BLAST OVERPRESSURE; 100,000 PEOPLE EXPOSED.

FIGURE 12

QUESTIONS FOR JACK REED

1. From Charles Hardin:

How does moisture content of the air affect the blast wave?

ANSWER:

We pretty much ignore it. To be correct, you should use a virtual temperature rather than a pure air temperature to calculate the sound speed. That's for the water vapor content of the air and just a correction in our refraction. On the other hand, what is usually referred to in questions of this type: Is the blast wave reflected off of clouds and off of precipitation? The answer is quite firmly, no. The drop size is not adequate to do anything other than give a very, very slight attenuation to the blast waves or the wave length that we are involved in here.

2. From E. A. Martell:

Will high speed westerlies above 30,000 feet in the isthmus area have similar accoustic wave effects as those experienced for high speed jet streams at higher latitudes?

ANSWER:

The jet streams in Nevada that we worry about in the wintertime which can cause focusing of blast waves and give troubles in Las Vegas are speeds that run typically 130 and occasionally as high as 200 knots in speed and I don't believe that our experience in the isthmian region or the tropical region show anything near this. The required speed for ducting from jet stream altitudes near the tropopause level where the temperature is very, very low--it gets down to as low as -100° C--then it requires at least 60 and generally over 100 knot speeds to overcome that and give you a wind ducted propagation. I'm not sure what the studies that ESSA is conducting are showing, but I don't think that there are very many wind speeds much over about 60 knots at that altitude, so I do not expect any jet stream ducting from 30,000 feet in the canal project. Our whole problem seems to be wrapped up in the ozonosphere propagation and caused by the winds up at 150,000 feet.

3. From E. V. Anderson:

What is the area of a focus zone?

ANSWER:

The calculated accoustic focus has zero width. You have infinite pressure over zero width. What the real result is we don't really know for sure, but we have some statistical information which says for jet stream ducting from the Nevada Test Site using a large number of small, high explosive tests, that within ± 10 miles of a calculated caustic, the average magnification came out to be, considering the ground reflection as part of the magnification, we got an average factor of 3.15. This is from 250 or 500 observations. It was 250 observations and I think the maximum of all these within 10 miles of the calculated caustic was about 8-1/2 for a magnification factor including the doubling by ground reflection which you always get. It's pretty much of a statistical thing. It doesn't come out as a nice, sharp focal point like you calculate by pure accoustics, but we're not dealing with pure accoustics, we're dealing with finite amplitude and long wave length waves and there's quite a bit of mix-up here. The atmospheric turbulence also scatters and diffuses it so pending more statistics, I think that you just need to say that within ± 10 or 20 miles of a calculated caustic, you can get this distribution of magnitudes which gives you some small, but finite probability of having a pretty large magnification on very, very rare occasions.

4. From W. J. Larkin:

Since the wave has directional properties, does the orientation of the "window panes" have an effect on damage potential?

ANSWER:

Yes, and this is mostly derived from Civil Defense housing tests and things like that. I believe, and John Blume may amplify this, but there is a factor of essentially 2 difference. You have on the side facing the blast about twice as much breakage as on the side of the house away from the blast. And on the sides of the house you have something in between. By the time you go out to where you are only breaking 1 out of 5,000 or 10,000 panes, this kind of gets lost in the statistics so you can't really identify it. I know one building in San Antonio we checked. I think there was a slightly larger percentage of windows broken on the back side than on the side facing the blast. So it is statistical and not very well defined.

GROUND MOTION PREDICTIONS

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ABSTRACT

Nuclear generated ground motion is defined and then related to the physical parameters that cause it. Techniques employed for prediction of ground motion peak amplitude, frequency spectra and response spectra are explored, with initial emphasis on the analysis of data collected at the Nevada Test Site (NTS). NTS post-shot measurements are compared with pre-shot predictions.

Applicability of these techniques to new areas, for example, Plowshare sites, must be questioned. Fortunately, the Atomic Energy Commission is sponsoring complementary studies to improve prediction capabilities primarily in new locations outside the NTS region. Some of these are discussed in the light of anomalous seismic behavior, and comparisons are given showing theoretical versus experimental results.

In conclusion, current ground motion prediction techniques are applied to events off the NTS. Predictions are compared with measurements for the event Faultless and for the Plowshare events, Gasbuggy, Cabriolet, and Buggy I.

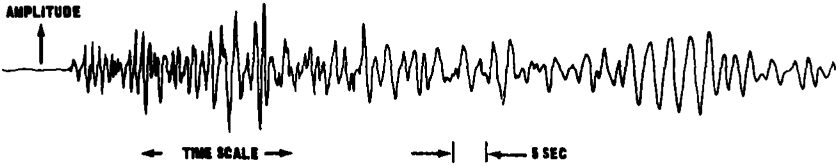
INTRODUCTION

Under contract with AEC's Nevada Operations Office, Environmental Research Corporation provides scientific and engineering support to the Effects Evaluation Division by predicting specified effects of planned underground nuclear explosions. With knowledge of the anticipated effects, safeguards are developed and safety is assured for persons and property within the affected range. In this discussion we will consider the directly induced seismic ground motion and techniques for its prediction. Ground motion predictions are required in order to assess the probability of damage to property and, more importantly, to preclude the possibility of personal injury.

Energy from an underground nuclear detonation is transformed into seismic waves which travel outward from the source in all directions. They follow several paths and display a variety of characteristics which can be related to effects on structures. Figure 1 shows a seismogram composed of various elastic waves arriving at a given point at different times. This might represent the vertical component of velocity measured at the surface of the ground at, say, 100 kilometers

FIGURE 1

SEISMOGRAM FROM AN NTS EVENT



from an event at the Nevada Test Site (NTS). Phases in the seismogram include the compressional and shear body waves at the leading edge of this trace and surface waves, such as the Rayleigh mode, at the trailing edge. Analysis of such wave forms requires separation and identification of the different modes, knowledge of their behavior in transit, and an understanding of the influence of source parameters. Analyzing ground motion data in this manner makes it possible to predict damage to structures, to forecast perception of ground motion by the general public, and to anticipate other effects such as damage to mines, wells, and slopes. With respect to this type of oscillatory ground motion, the remainder of our discussion will center on development of predictive technology and applications relevant to Plowshare events.

PREDICTIVE TECHNOLOGY FOR UNDERGROUND ENGINEERING APPLICATIONS

Source of Seismic Waves

Directly induced ground motion in the elastic region is a function of several variables, such as the energy and type of explosive, source point medium, depth of burial and geological medium properties. Within the immediate vicinity of the source the medium behavior is non-linear and complex due to high pressures and temperatures. From the (initial) vaporization cavity produced by the explosion a shock wave propagates, carrying about 50% of the available energy. For a 1-kt nuclear explosion, the vaporization cavity radius and pressure are approximately 2 meters and 1 million atmospheres, respectively, varying slightly from medium to medium.[1] As the shock wave propagates radially outwards, spherical expansion of the front and inelastic dissipation reduce the loading intensity to a point, at a distance called the elastic radius, where the elastic properties of the medium begin to play a significant role. The elastic radius is a function of the source point parameters, being a few hundred meters for a contained 1-kt nuclear event. From this point the medium behaves elastically and the phenomena may be described by linear theory. The waveform input to the elastic region may be considered to be a function of the elastic radius and the input pressure at this radius which in turn are functions of the source parameters. The frequency spectrum of the radiated seismic waves at the elastic radius is band-limited and also is a function of the source parameters.[2]

Most of the initial energy has been dissipated before reaching the elastic radius, and only a small percentage of the original energy remains to be propagated as elastic waves. In fact, published data for 20 large-scale chemical and nuclear explosions, ranging from yields of 1-kt to 200-kt show a range of conversions into seismic energy which varies from about 0.02% to less than 1%. The largest cratering experiment to date, Sedan, with a yield of about 100-kt, coupled less than 0.1% of its total energy into elastic seismic waves.[3]

In current ground motion prediction techniques, the total yield of a nuclear device is considered one of the few major variables in a conventional power law relationship. Postulated power law exponents for the increase of peak seismic amplitude with yield generally fall between 0.5 and 1.0.[4] Data from about 100 contained detonations at the NTS show peak seismic amplitudes that increase with yield to the 0.6 to 0.8 power. Variations in the exponent are attributed to source conditions, varied seismic wave modes and their paths, local geology of the recording site, and frequency of the ground motion.

Influence of the emplacement environment on peak seismic motions is not yet clearly defined. Factors which have been considered include depth of burial and the geologic medium. Some tentative conclusions, with exceptions noted, are that hard rock tends to couple more energy into the elastic region than unconsolidated media, and that increase of depth of burial, also, tends to increase the seismic efficiency.[5]

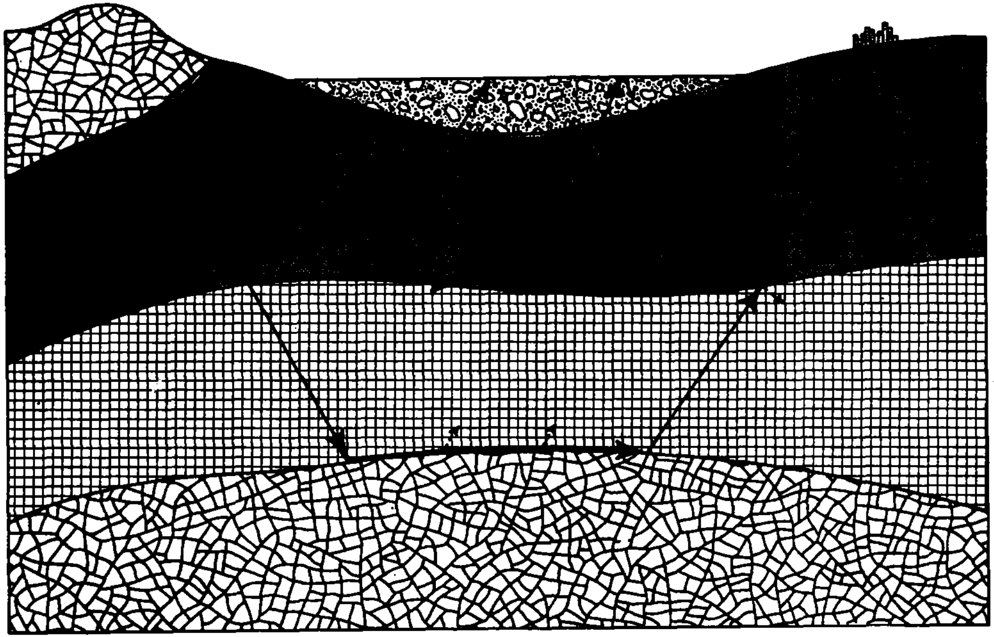
Transmission of Seismic Waves

A model for the transmission of seismic waves is shown in Figure 2. The seismic input to the elastic region has a frequency spectrum which is characteristic of the combination of all the source parameters. As the disturbance propagates through the earth, it encounters many geological boundaries. At each boundary, a combination of transmission, reflection and refraction of the energy occurs, depending on the angle of incidence and elastic constants of the media surrounding the boundary.

Other physical phenomena, such as wave mode conversion, reverberation within and between layers, scattering, and diffraction, occur along each transmission path and compound the complexity of the total

FIGURE 2

SEISMIC TRANSMISSION MODEL



process. Processes such as reverberation tend to introduce notches and resonant frequencies in the amplitude spectrum. Scattering causes attenuation which increases rapidly with decrease in wavelength of the pulse. This action causes the earth to act as a low-pass filter to seismic signals, and hence, reduces energy in the high frequency portion of the ground motion spectrum.[6]

The signal received at any particular location is not a single wave. It represents the combined effect of waves from all the different transmission paths within the crust of the earth. Spurious signals are also observed. They are related to wave groups arriving from random directions, such as near-surface waves impinging upon randomly-located near-surface inhomogeneities.

A final major factor in the signal amplitudes at any particular location is the influence of the surface geology at that location. Current NTS data indicate that stations located on some considerable depth of alluvium record amplitudes averaging about twice those recorded on adjacent hard rock sites. Individual station ratios of alluvium amplitude to hard rock amplitude range from 1 to 5, and are found to be frequency-dependent.[7]

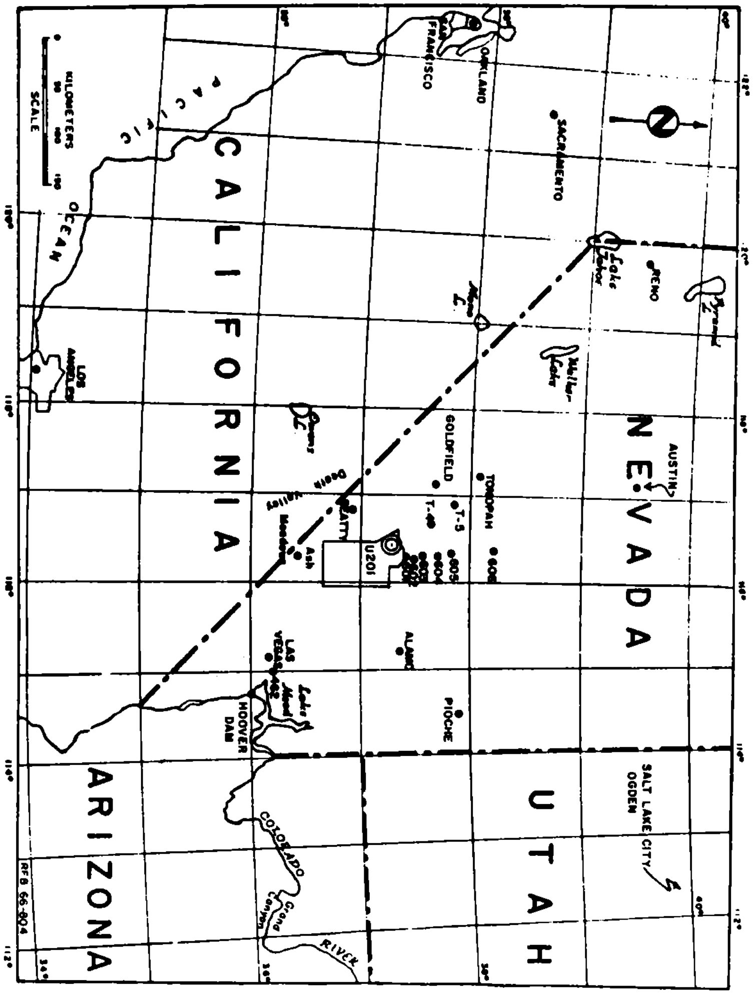
Instrumentation and Data Processing

Before discussing ground motion prediction methods, let us first consider the measurements program being conducted at the NTS. A large effort is currently in progress and programmed for collection of seismic data. These data are required for studies of variations in ground motion and their causes to complement the studies which have been conducted and those now in progress, and to verify the validity of the prediction methods.

Figure 3. The installation and operation of the seismic instruments are primary responsibilities of the Las Vegas Special Projects Party of the U. S. Coast and Geodetic Survey (USC&GS). Environmental Research Corporation and others provide plans designating the location and types of instruments required at each station. These plans are designed so that all centers of population in the vicinity of the NTS are instrumented, often at several locations in each city. The plans are also designed to collect data used to support the theoretical studies and to provide an understanding of ground motions for selected geologic conditions. A large detonation is usually monitored with about 100 recording stations.

The instruments used by USC&GS were selected because of their suitability for recording the essential information. They have a wide dynamic range and a broad band of response to frequency. However, each type of instrument has its own performance characteristics; one of the most important is the response to frequency. If the instrument does not respond as well to some frequencies as to others, the resulting

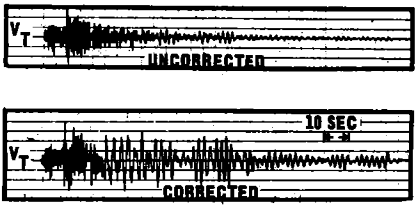
FIGURE 3
STATION LOCATIONS OFF THE NEVADA TEST SITE



seismograms will be distorted. Knowing the response to frequency of the various instruments, we have developed programs which remove (within signal-to-noise-ratio limitations) distortions produced by the instruments. An example of this is shown in Figure 4 where much of the low frequency information is lost without correction for instrument response. The data from some instruments do not need corrections because they respond uniformly to all frequencies of interest. Additional programs have been developed which produce acceleration and displacement seismograms from measured velocity seismograms.

FIGURE 4

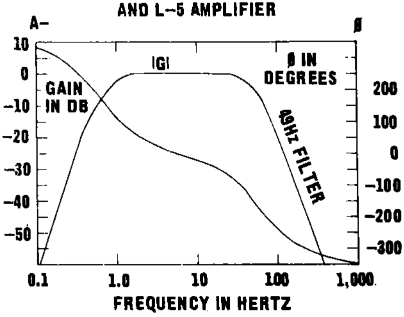
SEISMIC SIGNALS BEFORE AND AFTER CORRECTION



Some of the data processing which precedes the analysis will now be described.[8] Typical velocity measurements are recorded in the field on analog magnetic tape at two or three recording levels by USC&GS. Several field tapes are dubbed onto the tape that we process. This tape is previewed, the best data channels are selected, compensation is made for variable instrument gain, calibration is performed, appropriate seismometer response correction is made, and finally a master tape containing only usable, corrected data is generated. Velocity seismograms on the master tape are routinely processed to obtain peak amplitudes, ground motion amplitude frequency content, response spectra, acceleration and displacement seismograms, Fourier transforms, wave mode information and other selected parameters. This processing can be performed on an analog computer; or, the analog velocity traces are digitized automatically and the processing done on a digital computer.

The response characteristics of one of the velocity meters employed on the safety program is given in Figure 5. In our data processing we effectively lower the corner frequency of this instrument from 1 Hz to about 0.3 Hz.

FIGURE 5
RESPONSE CURVE OF VELOCITY METER
AND L-5 AMPLIFIER



Processing of the strong motion acceleration and displacement photographically recorded paper traces follows another course. These traces are digitized semiautomatically and run through an editing, calibration, and plot routine. The plotted, digitized trace provides an overlay trace for verification. Peak amplitudes, amplitude spectra and other parameters are then obtained by way of digital programs.

Statistical Analyses of Ground Motion

As a first attempt at establishing a significant relationship between underground nuclear explosions and resulting seismic motions, analyses were made of nuclear-generated seismic peak amplitudes recorded in and around the NTS.[4] We note that although the peak amplitude represents only one characteristic of a complicated ground motion, it is a good measure of the overall seismic signal strength. Using standard regression analysis techniques, we have developed prediction equations based on the data from previous detonations in similar environments to estimate the peak motions. Examples of these equations for stations on alluvial layers are shown in Figure 6.

We must question the applicability of such equations to events off the NTS, and also include cratering shots in our consideration. Later we will discuss applicable theories which are validated by this NTS experience.

* * * * *

$$a = k_1 W^{0.62} R^{-1.36}$$

$$u = k_2 W^{0.64} R^{-1.31}$$

$$d = k_3 W^{0.77} R^{-1.14}$$

where W = yield; R = distance
a = peak surface acceleration
u = peak surface velocity
d = peak surface displacement
$k_{1,2,3}$ = regression constants

Figure 6. Peak Amplitude Prediction Equations, Alluvium Stations

We now know that we can predict peak motions within acceptable limits but the frequency content of the seismic motion to which structures respond must also be predicted; otherwise, only a rough estimate can be given for the associated structural response. Again, on a statistical basis, we have developed the capability to predict two kinds of seismic spectra.[9] The first is a measure of the seismic amplitude-frequency content which is, for practical purposes, independent of the duration of the seismic signals. The second, which I shall describe here, is the spectrum obtained by plotting the peak response of single degree-of-freedom system as a function of the center frequency of the system. For each frequency, the seismogram is used as the input signal. The value of this type of predicted seismic spectrum is that it is used to determine estimates of structural response over a large area surrounding the detonation point. Statistical analysis of the response spectrum amplitudes at several frequencies, as a function of yield and distance dependence (similar to the peak motion equations shown above), reveals that both the yield and distance dependence are functions of frequency. As anticipated, higher frequencies attenuate more rapidly with distance, and the lower frequencies increase slightly more rapidly with yield. A response spectrum prediction based on this statistical analysis is shown in Figure 7 for a Las Vegas station. Also shown on the figure for comparison with the prediction is the observed response for the Benham event.

Presently we are developing techniques to predict complete seismograms. This will allow determination of the response of any structures for which mathematical models are available. To date several seismograms have been synthesized having characteristics very similar to those of real seismograms. An example is given in Figure 8.

FIGURE 7
PSEUDO RELATIVE VELOCITY SPECTRA,
BENHAM EVENT, SE-6 STATION

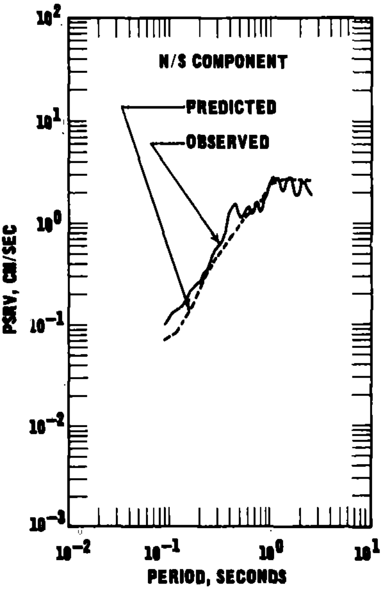
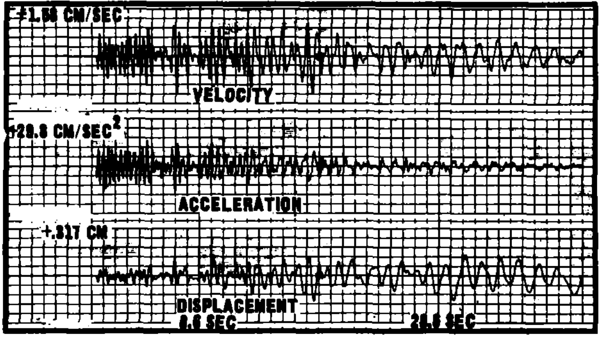


FIGURE 8
SYNTHETIC SEISMOGRAM CORRESPONDING TO A STATION ON ALLUVIUM
DISTANCE: 50 KILOMETERS
YIELD: 100 KILOTONS



The results indicate that synthetic seismograms can be constructed such that each:

1. has nearly the same Fourier amplitude spectrum as that of given seismic records of the same yield and range;
2. contains the same frequencies in the same descending order as real seismograms;
3. produces similar band-pass filter (BPF) and pseudo-relative velocity (PSRV) curves comparable with those of real seismograms; and
4. reacts with model structures in a manner comparable with the real seismograms.

DEVELOPMENT OF PREDICTIONS FOR EXCAVATION AND OFF-SITE APPLICATIONS

Applicability of these techniques to new areas, including cratering as well as underground shots, has been a logical source of concern. Fortunately, the AEC continues to pursue a comprehensive study program to improve prediction capabilities primarily in new locations outside the NTS region. A few of these studies will now be described.

Transmission Models

The objective of wave mode studies[6] is to correlate the observed ground motion recorded at various stations with individual elastic wave modes having a specific travel path. The first problem, then, is to identify these modes. Wave mode identification is based primarily on the large body of theoretical and observational knowledge acquired by seismologists. Figure 9 shows a good example of one type of mode identification utilizing properties of the radial-vertical product waveform, taken from the Boxcar event.

The product waveform at the bottom of the figure displays compressional (negative pulses at the leading edge), shear (positive pulses at about 10 seconds), and Rayleigh modes (oscillatory wave with twice the frequency of the surface wave on the radial and vertical tracer). These product waveform characteristics are a direct consequence of the particle motions associated with the classical wave types.

FIGURE 9

PARTICLE VELOCITY SEISMOGRAM AND RADIAL-VERTICAL COMPONENT PRODUCT WAVEFORM

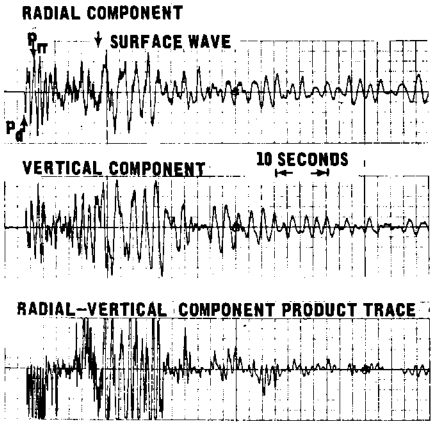
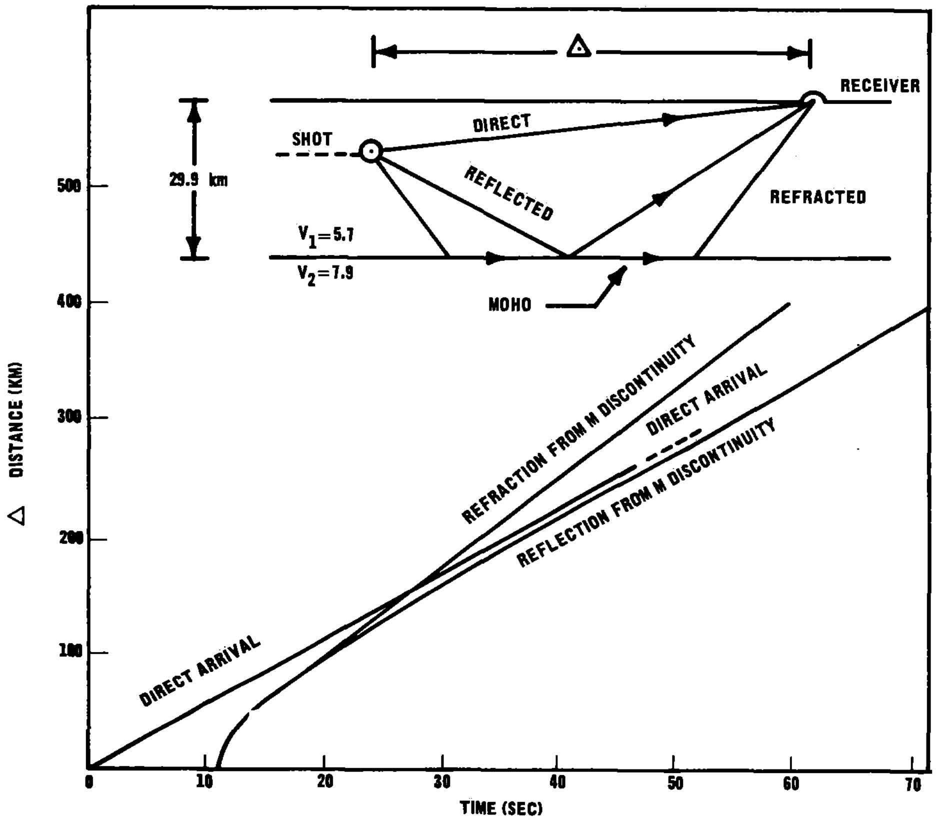


Figure 10 shows a simplified model of the earth's crust in the NTS area generated with the aid of wave modes observed in an around the NTS. Also shown are the relative travel times for three of the elastic wave modes (a direct P wave, refracted P wave, and a reflected P wave) generated by a nuclear detonation. The model has parameters of velocity and crustal thickness similar to those observed and derived at NTS by other investigators. The major point of interest is the fact that different wave modes arrive at a surface location with varying but predictable relative times in direct relationship to the physical properties of the earth, the depth and physical characteristics of the Mohorovicic discontinuity, and the distance of the recording site from the nuclear detonation.

The presence of a layer of unconsolidated material, such as alluvium, can cause substantial amplification of the magnitude of observed seismic signals. This effect, however, is a complex function of both the wave mode and the frequency so that a simple, statistical correlation of observed effects can be of only limited usefulness, especially if predictions are required at new locations. Therefore, a fundamental investigation[7] was undertaken of the propagation of different wave modes in an alluvial layer.

FIGURE 10

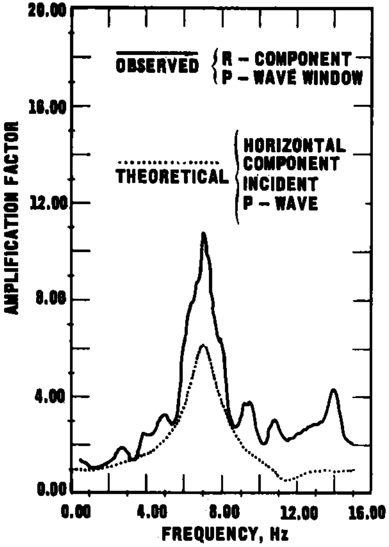
TIME—DISTANCE CURVES – NTS CRUSTAL MODEL



The aim is to predict the effect of the layer on the Fourier amplitude spectrum of the observed surface motion. Models for Love and Rayleigh surface wave amplification, as well as for P and S body wave amplification, have been formulated and preliminary validation with test results is good. Figure 11 indicates comparison of theory with experiments for the relative amplification of the P-wave radial components measured at a pair of stations in Tonopah, Nevada.

FIGURE 11

TONOPAH AMPLIFICATION FACTOR
(R COMPONENT, P – WAVE WINDOW)



The predicted resonant frequency for the station on the unconsolidated material is 7 Hz, substantially the same as the measured value. At resonance the predicted level of amplification is a factor of six and the measured value is a factor of 11. Use of further instrumentation to provide a better check of this theory is part of ongoing effort. These studies will provide an effective means for improving the predictions of frequency dependent phenomena (for example, PSRV response spectra) at sites located on alluvium. The value of such accurate prediction of resonances associated with surface geology lies in the ability to make provision for potential structural damage.

I should like to return now to the validity of the seismic scaling exponents statistically derived on the basis of NTS data. In particular, we should like to have a valid theoretical description of the behavior of seismic amplitudes at each frequency as a function of distance from the source and as a function of source yield. A recent effort to describe the seismic amplitude dependence on the distance variable is proving fairly successful. Briefly, the earth is treated as a heterogeneous medium model[10] in the sense that the elastic constants and the density are treated as random variables. Wave propagation in this model is solved for the case of a step function (sudden initial pressure which decays with an infinitesimal decay constant) applied to a spherical boundary. At large distances, for the case of a homogeneous medium, the displacement solution is a damped sinusoid which has a characteristic wave length proportional to the spherical radius. In this heterogeneous case, a different length, the correlation length, appears. This is defined as the distance over which the density and elastic properties of the medium change substantially. For wave lengths greater than the correlation length, the medium appears homogeneous; for wave lengths less than the correlation length, there is an exponential selective frequency decay with distance (due to scattering). This frequency selective attenuation with the distance variable is in qualitative agreement with the experimental trend observed in the NTS data.

Seismic Spectrum Scaling with Yield

A related model has been developed for the theoretical description of the behavior of seismic amplitudes at each frequency as a function of source yield.[11] In this model, the influence on ground motion spectra of source parameters such as yield, depth of burial, and medium type, have been considered. Compared with the heterogeneous model, the source function is an exponential function applied to a spherical boundary.

It is found that for a specific medium the explosive yield exponent is frequency, depth, and yield dependent. For the particular case of underground explosions at set scaled depths, the yield exponent decreases with increasing frequency at a constant yield and decreases with increasing yield at a constant frequency. Also the bounds of the exponent are medium dependent. Comparison with the response spectrum yield exponents statistically derived from NTS data for a large number of events, as well as with specific events, shows good agreement. In a general way, this theory explains the experimental evidence that smaller yield shots at a set scaled depth in a particular medium generate higher frequency ground motions that higher yield shots; and that shots at a set yield in a particular medium generate higher frequency ground motions the greater the depth of burial.

APPLICATION TO OFF-SITE EVENTS

Application to off-site events will be shown by comparing predicted and measured response spectra.

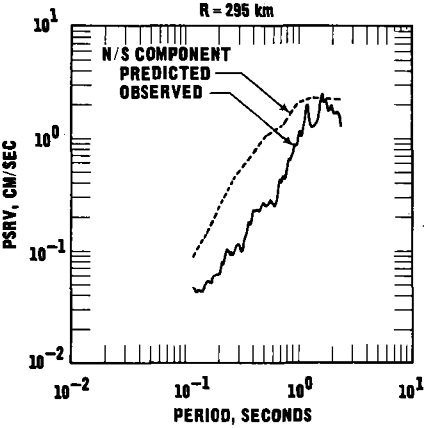
Underground Events

Figure 12 shows the response spectrum at a Las Vegas station, generated by the Central Nevada Faultless event.

FIGURE 12

PSEUDO RELATIVE VELOCITY SPECTRA; FAULTLESS EVENT: SE-6 STATION

R = 295 km



The level of the predicted (upper) curve is seen to be slightly conservative for this station, some 295 kilometers from the source, and the shape is seen to be a fair approximation to the measured curve. Numerous comparisons of Faultless ground motion predictions indicated no big surprises in application of NTS data statistics to this off-site event which occurred at a typical depth of burial.

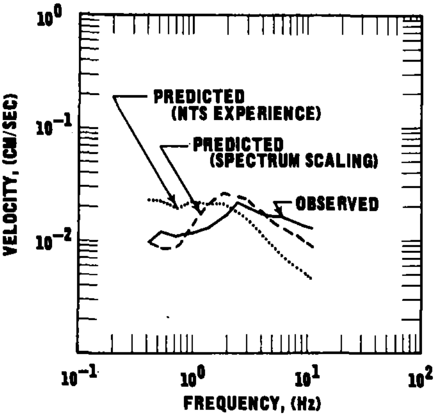
The composite spectrum for stations at 90 km, generated by the northwestern New Mexico Gasbuggy event,[12] is shown in Figure 13.

NTS experience delivers a prediction which is significantly improved when the theoretical spectrum scaling is taken into account.

The parameter that departs most from NTS experience is the depth of burial which, for the Gasbuggy event, is greater than typical NTS experience.

FIGURE 13

SPECTRA FOR STATIONS AT 90 km; EVENT GASBUGGY



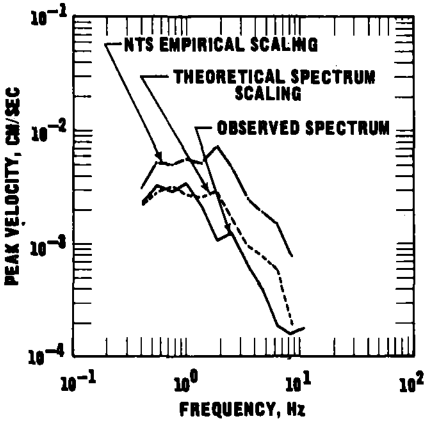
Excavation Events

In Figure 14 are shown response spectra at a station in Las Vegas, associated with the Cabriolet cratering event.[5]

The prediction based on NTS experience also is improved significantly when theoretical spectrum scaling is included. Here, as with Gasbuggy, the parameter that departs most from NTS experience is the depth of burial which, for the Cabriolet event, is smaller than typical NTS experience.

FIGURE 14

COMPARISON OF THEORETICALLY AND EMPIRICALLY SCALED SPECTRA, EVENT CABRIOLET. RADIAL COMPONENT; SE-6; ALLUVIUM

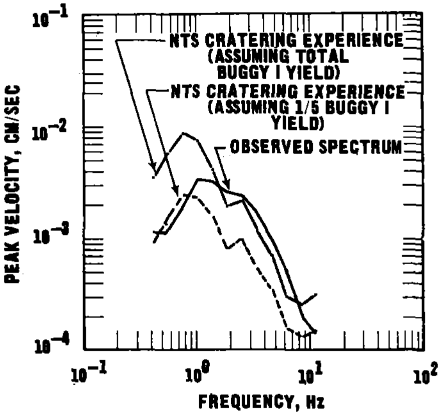


An unusual source of configuration, pertinent to several engineering applications, is represented by the nuclear five-element row charge, Buggy I. Treating the seismic data as if it were caused by a single source of energy equal to the total energy in the row charge, delivers interesting results which can be seen in Figure 15.

The upper curve, based on NTS single source cratering experience, is noticeably higher than the observed spectrum at frequencies below 1 Hz where significant energy exists. In fact, in this frequency range, the measured spectrum is more closely approximated by that which would be anticipated with only one row charge element, as seen by the lower curve. Above 1-1/2 Hz, the prediction based on the total Buggy I yield is satisfactory. An in-depth report analyzing these interesting results is in preparation.

FIGURE 15

SPECTRA FOR BUGGY I; SE-6 STATION



CONCLUSIONS

In conclusion, then, we see that much of the technology is available for making sufficiently accurate predictions of the directly induced ground motion resulting from underground and excavating nuclear detonations. However, some work does remain in order to obtain correlation of ground motion with a wider range of geological and geophysical parameters.

REFERENCES

1. Higgins, G. H., and Butkovitch, T. R., "Effect of Water Content, Yield, Medium and Depth of Burial on Cavity Radii," UCRL-50203, 1967.

2. Beaudet, P. R., Cassity, C. R., Davis, A. H., and deCaprariis, P. P., "Predicting the Effect of Underground Nuclear Explosions," ERC Report, NVO-1163-165, 1968.

3. Mickey, W. V., "Operation Plowshare, Project Sedan: Seismic Effects from a High-Yield Cratering Experiment in Desert Alluvium," AEC, PNE-213F, February 1963.

4. Murphy, J. R., and Lahoud, J. A., "Analysis of Seismic Peak Amplitudes from Underground Nuclear Explosions," ERC Report, NVO-1163-166, 1968.

5. Klepinger, R. W., and Mueller, R. A., "Analysis of Ground Motion, Cabriolet Event," ERC Report, NVO-1163-178, 1969.

6. Hays, W. W., "Identification of Elastic Wave Types on Seismograms from Underground Nuclear Explosions," ERC Report, NVO-1163-157, 1968.

7. Davis, A. H., and Murphy, J. R., "Amplification of Seismic Body Waves by Low Velocity Surface Layers," ERC Report, NVO-1163-130, 1967.

8. Watson, D. L., "Procedure for Recording Ground Motion Velocity from Underground Nuclear Explosions," ERC Report, NVO-1163-93, 1967.

9. Lynch, R. D., "A Summary of Prediction Equations Derived from Band-Pass Filter Data," ERC Report, NVO-1163-152, 1968.

10. Beaudet, P. R., "Wave Propagation in Heterogeneous Media," Presentation and Handout at NVOO Panel of Consultants Meeting, March, 1968.

11. Mueller, R. A., "Seismic Spectrum Scaling Law," Oral Presentation to be presented at 50th Annual Meeting of American Geophysical Union, April, 1969.

12. Klepinger, R. W., "Analysis of Ground Motion and Containment Data, Gasbuggy Event," ERC Report, NVO-1163-158, 1968.

13. Cassity, C. R., and Klepinger, R. W., Buggy I Ground Motion Analysis Study, ERC Report to be issued.

QUESTIONS FOR PETER LOUX

1. From R. Duff:

   Can HE tests be used at a new site to help determine propagation paths and modes?

   ANSWER:

   I don't claim to be an expert on the equivalents of HE and nuclear generated seismic motions, however, I would think that the way you phrased the question that yes, you probably could determine something about the wave mode propagation from an HE charge. I think the only place you might get into trouble is if you were trying to equate the seismic spectrum that you would expect to get from a nuclear charge from the one you measured from an HE charge.

2. From Mr. C. Nelson:

   What is the average speed in miles per second in which the seismic motion or signal is propagated from an underground detonation?

   ANSWER:

   Why don't I just give you some numbers I remember and you can convert it yourself. Let's take the refracted wave along the end discontinuity which is out beyond the critical distance of which, at the Nevada Test Site, is about, as I recall, 100 to 150 kilometers. If you are outside that range, the refracted arrival spends most of its time in the upper mantle at a velocity of something like 8 kilometers.

3. From Alex Grendon:

   How did the direction of the row of charges in Buggy I compare with the direction to SE-6 station?

   ANSWER:

   I don't know off-hand, but I certainly can say something about the directional properties of this charge, since I just finished a report on trying to identify interference effects from the Dugout HE charge. We looked for two things in the seismic information--off the end of the row versus perpendicular to the row. We tried to find linear, so called classical linear, interference to see if any were present or not, and that experiment was inconclusive because the frequency that we needed to observe for interference was somewhat in the noise of the seismic signal and perhaps partly because the interference was not present at all. The other part of the experiment was to determine if we could use the seismic reciprocity theorum on this kind of seismic data--say broadside versus end fire. So what we did was, having been unsuccessful on the Dugout experiment, we requested and received instrumentation on two arcs--two quarter circles coming from the end of the Buggy row to the center, one at a distance of 5 to 10 kilometers and the other was out farther and we did not find--so far we are still working on it--we haven't found either reciprocity or the classical linear interference principles applicable here. Of course, you start thinking about where you're shooting in the source region; it's really a non-linear problem you should be looking at to see what the non-linear shock-wave is pumping into the elastic region off the end versus broadside.

4. From Alex Grendon:

   Is this directional factor theoretically important?

   Moderator: I just checked with Mr. Reed. We were trying to ascertain the orientation of the buggy row charges and our best recollection is that it was oriented about north 70 east. That was the row. The direction from Las Vegas to the row charge is about north 27.

   ANSWER:

   In other words the direction to Las Vegas is more broadside than it is off the end.

5. From F. Gera:

   Can you please comment on the possibility of applying the mentioned spectrum prediction technique to natural earthquakes?

   ANSWER:

   Actually we have, in fact, looked at a few earthquake spectra. El Centro is one and some others recorded by the Coast and Geodetic Survey at about 100 or 200 kilometers from the epicenter and so far, and I certainly wouldn't want to be misquoted here and more work needs to be done on this point, but so far we haven't found large differences in the seismic spectrum from an earthquake whose equivalent yield, and this is rather tenuous to take the magnitude and find an equivalent magnitude-yield relationship which you can do from say 50 of the reported magnitudes reported by the Air Force, for example. If you convert the magnitude over the yield and then plug the yield into the prediction equations which deliberate spectrum and compare that to the spectrum of the earthquake motion, the few cases that we've tried don't show any large differences between the nuclear and earthquake generated motion. However, one would have to look for differences if you were closer in to the source for example, because obviously the source function has got to be different.

GROUND MOTION EFFECTS

by
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ABSTRACT

Ground motion caused by natural earthquakes or by nuclear explosion causes buildings and other structures to respond in such manner as possibly to have high unit stresses and to be subject to damage or--in some cases--collapse. Even minor damage may constitute a hazard to persons within or adjacent to buildings. The risk of damage may well be the governing restraint on the uses of nuclear energy for peaceful purposes. Theory is advanced regarding structural-dynamic response but real buildings and structures are complex, highly variable, and often difficult to model realistically. This paper discusses the state of knowledge, the art of damage prediction and safety precautions, and shows ground motion effects from explosions of underground nuclear devices in the continental United States including events Salmon, Gasbuggy, Boxcar, Faultless and Benham.

* * * * * * * * * * * * * * * * * * *

Ground motion, whether caused by natural earthquakes or underground nuclear explosions, causes buildings and other structures to respond and to be stressed. Depending upon the amount of the response, the duration of the motion, and many other factors, the structures may be subject to damage or, in extreme cases, to collapse. In addition, ground motion can cause or accelerate soil or rock slides and it can induce waves on bodies of water such as lakes or reservoirs. Severe ground motion could also rupture underground pipelines and sewers. It is essential that these effects be predicted in advance so that effective means can be taken to minimize or prevent damage and to eliminate hazard to persons. The public health would indeed be impaired if occupied buildings suffered damage without warning.

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*President, John A. Blume & Associates Research Division, San Francisco, California

THE RISK AND ITS CONTROL

It has become clear in recent years that structural response to ground motion constitutes a risk that is much more important in the nuclear field than was originally contemplated. In fact, it may well represent the limiting restraint on the yield level for planned events except in desolate areas. An additional problem--even without significant damage--is the matter of public reaction to ground motion and to its effects. Education, briefings, new releases and courtesy can be most effective in this regard.

In order to cope with ground motion effects currently and also to develop improved technology for the future, the Atomic Energy Commission, Nevada Operations Office, Effects Evaluation Division, conducts with the aid of its contractors continuing activity in seismic problems. John A. Blume and Associates Research Division is concerned with all aspects of structural response and surface effects for Nevada events and for other events in populated areas. The scope of the work includes all possibly affected surface structures and features. We also do long range research in related problems and provide various services prior to, during and after detonations. We observed the 1964 Salmon event in Mississippi since we had not been in the program long enough to participate as we have on all subsequent events at the Nevada Test Site, and on offsite events such as Gasbuggy, Faultless, Sterling, and Rulison now in progress.

A great deal has been learned and yet there is still much to be done. Some of the effort depends upon knowledge derived from natural earthquakes over the years. We have been in that field for 3½ decades. However, because of certain differences between the problems and the technologies associated with natural earthquakes and with manmade ground motion, new techniques and much greater accuracy and care are essential with the nuclear problem. A careful, step-by-step program has been conducted to acquire needed data and to improve the technology before crossing various thresholds.

It must not be inferred that all the risk is associated with highrise buildings, although these buildings are the most sensitive to distant energy releases. There are a great many more low buildings, commercial and residential. This statistical exposure increases the probabilities of unusual occurrences. A particular problem, especially with low buildings, is that there usually are minor cracks or other defects of which the owner isn't aware until he feels the building move. Most of these, however, can be categorized as to time or cause by careful examination. There are often latent conditions that would lead to cracks or other problems whether or not the ground was vibrated. The motion, however, even at low levels, may trigger the existing mechanism sooner than under normal conditions. The total distress may well be no more after a period of time than if the ground motion had not occurred.

Figure 1 shows the principal area of seismic field activities in the south and central portion of Nevada. The large NTS events cause significant motion in the bordering communities shown and also in Las Vegas, the largest city in the area. Of course, we have to be aware of all installations whether or not they are in communities. Our work within the test site is generally limited to test buildings, certain buildings which we monitor, and the Nuclear Rocket Development Station facilities at Jackass Flats. The map also shows the Central Nevada Testing Area which was the site for the Faultless event for which we considered many cities and towns not shown, including Salt Lake City, Reno, Sacramento, etc. As yields increase the area of interest also increases.

RESPONSE DYNAMICS

Because of the initial sparsity of strong nuclear ground motion data we utilize all possible information from the earthquake field in which we have been engaged for decades. There are similarities--and also differences--between natural earthquake and manmade ground motion data and procedures. Figure 2 shows the measured motion of one of the strongest earthquakes ever recorded. The USC&GS recorded the acceleration time history shown on the upper diagram. The velocity and displacements were obtained by integration. The periods, or pulse durations, increase with integration as shown by the number of zero crossings.

Six simple vibrating systems are shown in Figure 3. Motion can be induced by displacing the base or the ground as indicated. In the elastic range in which no damage occurs the natural periods of the first five systems would not change with amplitude. However, if the rocking block were on a rigid base, its frequency would increase as amplitude decreases. Real buildings are quite complex and yet they can be modeled reasonably well in some cases. The important properties are natural periods, damping, mode shapes, elastic strength, and inelastic properties beyond the linear range.

A basic principle in dynamics is amplification under resonant, or "tuned" conditions. Figure 4 shows steady state response under the continuous forcing of ground motion. If the ground motion period coincides with that of the structure there is perfect tuning at a ratio of 1.0. In this case, only damping or energy absorption limits the response. With no damping, the theoretical response is infinite. Most modern buildings have low damping ratios--in the order of 2% to 5% of critical, where critical refers to the amount that would just prevent free vibration. Fortunately, there is seldom perfect tuning or sustained periodicity of ground motion. However, real building responses are greatly amplified and resonant amplification is a real problem because perfect tuning is not required for response motion to greatly exceed the ground motion.

In practice we do not deal with simple systems or simple ground motion; both are quite complex. The analysis requires extensive mathematics and large, high speed computers. One very useful device is the response spectrum which shows at a glance how various idealized simple oscillators would respond to a particular time-history of ground motion. Figure 5 shows how oscillators of various natural periods and each with 5% of critical damping would respond to ground motion recorded at the NRDS facility at the test site. For example, an oscillator of 0.2-second period would have had a peak acceleration of about 0.10g. Because real buildings are not simple oscillators various corrections must be made in applying such response spectra.

The response spectrum may be in terms of acceleration, velocity, or displacement. If one assumes the building is moving in harmonic motion there are simple relationships between acceleration, velocity, and displacement and one may consider them all at once on one plot. Figure 6 shows such a plot for event Greeley as recorded at the NRDS facility. Two damping values are shown, 2% and 10%. Note how greater damping decreases and smooths the response. For 10% damping, at a period of 2 seconds, the relative response velocity is 3.4 cm/sec, the acceleration about 0.01g and the relative displacement about 1 cm.

RESPONSE SPECTRA

The response spectra for several real earthquakes are shown in Figure 7 together with the Boxcar and the Faultless spectra for Las Vegas, station SE-6. All have 5% damping. The El Centro earthquake of 1940 was very strong and caused considerable damage in the short period range. There were no buildings in the long period range. The Los Angeles response to the Taft earthquake of 1952 caused about $10,000,000 worth of damage to limited height buildings situated some 80 to 100 miles from the epicenter. The Fairbanks earthquake of 1967 caused damage to buildings in the short period range. The earthquake shown as Sacramento 1966 occurred near Truckee, California. This spectrum is very interesting because new highrise buildings having periods in the order of 1 second were just at the threshold of minor damage. It is also to be noted that this response in the range of 1 to 2 seconds is very close to that of Boxcar in Las Vegas for which no real damage has been reported. There are reasons to believe that Boxcar was close to a threshold of damage, perhaps at a 3-or 4-sigma probability. The Faultless event, as shown, was much less severe in Las Vegas than Boxcar.

There was some minor damage in Hattiesburg, Mississippi, from nuclear event Salmon in 1964. The response spectrum is shown in Figure 8. Also shown in the response spectrum for Boxcar in Las Vegas. There was no real damage in Las Vegas, although over 100 complaints were received. This is an example of the fallacy of using peak values as criteria without regard to period. The low buildings in Las Vegas (short periods) have received far less energy than those in Hattiesburg even though the Las Vegas peak velocity is somewhat greater than Hattiesburg. Acceleration is more meaningful for low, rigid buildings. Note that the Las Vegas acceleration was much less than at Hattiesburg in the short period range. The relative displacements in Las Vegas have been much greater than in Hattiesburg. This affects the long period, tall buildings, of which there are many in Las Vegas.

Figure 9 shows the Las Vegas response spectra for the three largest NTS events to date, Greeley, Boxcar and Benham. Note that in some period bands one event will have the greatest response while at other periods another event will have the greatest response. This is especiallv true between Greeley and Boxcar. Since buildings respond sensitively in accordance with their natural periods, these variations are very important. Broad generalizations can be very misleading for particular cases.

Figure 10 is another way of looking at statistical variations. These curves are not spectra but upper and lower envelopes of 8 spectra--all 5% damped, all for one event, Benham, and all in Las Vegas. These are for horizontal motions at four different stations, all on desert alluvium, and about 4 miles (maximum) distance apart.

Since the range to the shot point was over 100 miles, its variations to the four stations are insignificant. Also interesting is the fact that different stations and components control the envelopes at various period values. Statistical variations and probabilities must be considered in predicting response to ground motion.

Figure 11 shows 10% damped response spectra for project Gasbuggy at five different stations. The radial distances from ground zero are shown in the figure. Note that at Farmington, 90 kilometers out, the motion at 1-second period approaches the acceleration of stations only 34 kilometers our from GZ.

Figure 12 shows response spectra in various cities for event Faultless detonated in Central Nevada in 1968. The designation SE-6 is for a Las Vegas station. The motion was felt by some persons in tall buildings at Salt Lake City, 440 kilometers away.

The more people sense ground or building motion the more they are apt to become frightened unless pre-warned and the more they will complain about possible damage. For this reason, and also to obtain a better coverage of motion over broad areas without the need for excessive instrumentation, we have studied the threshold of human perception of motion. Figure 13 shows new data recently obtained in our laboratory in the long period range of 1 to 5 seconds typical of tall buildings and how this information adjoins previous data obtained by others in the short period range. It was found that acceleration is the best parameter for human reaction to motion. The heavy curve indicates the mean regression line and the lighter curves the variations at plus or minus one standard deviation.

BUILDINGS, RESPONSE AND DAMAGE

Figure 14 is a "threshold ladder". It has no scale but it does indicate the various levels of interest. There is usually a big gap between human perception of motion and the onset of damage. Many people in Las Vegas buildings have felt the largest NTS events. The problem is to define the damage levels. Actually, they vary greatly depending upon many parameters. One of our major objectives is to determine these thresholds over the entire spectrum of conditions. There is no reliable formula, criterion, or rule of thumb, although many have been proposed.

In estimating damage and in considering safety it is essential to know something about the inelastic characteristics of materials and buildings. It makes a big difference whether an overstressed material is brittle and will fracture or whether it is ductile and will simply crack and stretch. Figure 15 illustrates a ductile frame and a brittle wall. The relative energy absorption characteristics of these two systems may be judged by the area under the force-deformation curves. Often, the two types of systems are combined in real buildings. A building subject to sudden collapse must be treated differently--safetywise--than one that might deform but not collapse.

A 15-story building has mode shapes as shown in Figure 16 for the first three modes. The building would respond to ground motion depending on the frequency content of the ground motion. This particular building responded largely in its third mode to a local earthquake in 1957. The circles indicate where instruments measured the motion.

Figure 17 indicates how a 4-story building can be idealized mathematically as a system of lumped masses and weightless springs. Note that if the floor system is flexible (as they are in most contemporary buildings) the system is far coupled and indeterminate. The stiffness matrix contains 10 different elements. Models like this are used to compute the response to complete time-histories of ground motion.

The data in Figure 18 are for a Las Vegas highrise building. The squares represent measured response to NTS events. The mean peak top level acceleration is about 7 times the peak ground acceleration. Empirical predictions can be made with such regression line analysis when important parameters are essentially constant. This is one way to extrapolate. The points shown generally fall within one standard deviation except for the small events for which measurements are less accurate and more affected by "noise" or non-event conditions. Care must be taken to note new trends in such data. There are reasons why the linearity indicated may not prevail at greater motion.

The spectrum curve shown in Figure 19 is for response to Las Vegas ground motion, 2% damping, event Knickerbocker. The circles represent the measured response of tall buildings in the same event after correction for participation factor and modal combinations. The general correlation of the circles and the line is good, although there are variations for some buildings. We frequently compare theoretical results with measured data and explore any anomalies.

We also use more exotic prediction methods than empirical and spectral response, although such are generally reserved for special cases or studies. One of these methods is the rigorous "time-history" procedure wherein a complete model of a real building is subjected to the complete time history of the ground motion as a forcing function. Figure 20 compares measured top-level motion in a 21-story building to the same motion computed independently with the building model and the ground motion as measured some distance away from the building. The comparison here is excellent--in the amplitudes, the periods, and in the time scale. This indicates that the building was well modeled. The results are not always this good. Large, fast computers are necessary for such complex computations.

DAMAGE ESTIMATION

With no damage there is no hazard to persons. The motion itself is not of sufficient intensity or duration to cause physical harm. It is necessary to estimate the type and degree of damage, if any, as a means of determining whether evacuation should be recommended, or if those working on scaffolds should be cautioned; or perhaps whether temporary bracing should be employed locally; or perhaps whether any of these steps is indicated.

We have developed methods of estimating damage, or lack of damage, which take into account--in an orderly manner--the important theoretical and practical aspects of the complex problem. Given a whole exposure of ground motion from a large event, what are the probabilities of damage and the damage forecasts for all the various communities and types of structures and soil conditions? This is a problem involving structural theory, dynamics, soil conditions, joint probabilities of demand and capacity, and many other factors. The Spectral Matrix Method which we have developed uses predicted response velocities in 8 period bands as shown in Figure 21. It also includes 12 velocity rows as shown to form a 96-element matrix of "demand". In addition, the various types of structures are assigned yield point "capacities" in terms of pseudo spectral response velocity, inelastic characteristics, reserve energy capacities in the damaging range, and damping values, usually 5% of critical. The "exposure" represents the replacement cost of all the structures in each area. Demand and capacity are assigned probability distributions and the probabilities are computed for demand to exceed capacity, in which case damage begins. The output is damage for each community and category of building. This procedure is limited only by the available data on real buildings and ground motion. It has been extended to cover multiple shots from various locations.

There are many probability problems inherent in damage estimation. The small figure in the lower right corner of Figure 22 indicates demand in discrete values for convenience here. This is ground motion, generally highly skewed as shown. The ordinate is probability. The small figure at the upper left is for the structural capacity. The probability distribution is often similar to Gaussian, but, of course, without negative values. The large 3-dimensional schematic diagram shows the joint probability of all combinations of demand and capacity. The height represents probability, with the volume being unity. If DEM/CAP is less than 1 there is no damage. If it is more than 1, the damage extent varies in some manner as DEM/CAP. In the schematic shown, there is a small probability of damage. One must be concerned with low capacities getting together with high demands. This operation is included in the Spectral Matrix Method of Damage Prediction. It has been extended to estimate damage in a whole country, from multiple shots, as in damage and safety studies for the proposed interoceanic canal.

If there is a sufficient probability of damage we may recommend evacuation to AEC, NVO. We may in other cases recommend precautionary procedures or warnings to persons in that particular area. The actual warning to the people and the conduct of any evacuation measures by the U. S. Public Health Service is the responsibility of the NVO Test Manager. Temporary closure of roads through an area is sometimes recommended because of possible slope failure, rock falls, or perhaps because of the possibility of damage to the road itself. In such cases local highway patrol offices or the county sheriff's staff may be called upon by the Test Manager to establish road blocks and to advise motorists of delays or alternate routing.

Predictions of ground motion effects with safety recommendations are made before every major event at the NTS and all offsite events in populated areas. These follow preshot surveys and complete coverage of all possible hazardous conditions or structures. During the events, instrumental records are obtained at strategic places, and observers are stationed at locations of special interest. Following events, re-surveys are made to check for possible damage. A report is prepared to show how the actual response compared to the predicted, in view of the actual ground motion. This sharpens prediction capability and adds to the long range technology. Any complaints of possible damage are carefully and courteously investigated and every effort is made to determine the real cause or causes of any existing trouble. If it can be shown that the ground motion could have caused the trouble, it is the policy of AEC to make appropriate settlement.

All data obtained during and after the event, including the instrumental records, are carefully analyzed and permanently recorded. In many cases, detailed analyses are conducted. All of this adds to and advances the basic technology of predicting the effects of ground motion. The overall effort is conducted with checks and balances and scientific objectivity. Much progress is being made while, at the same time, observing the public welfare and safety.

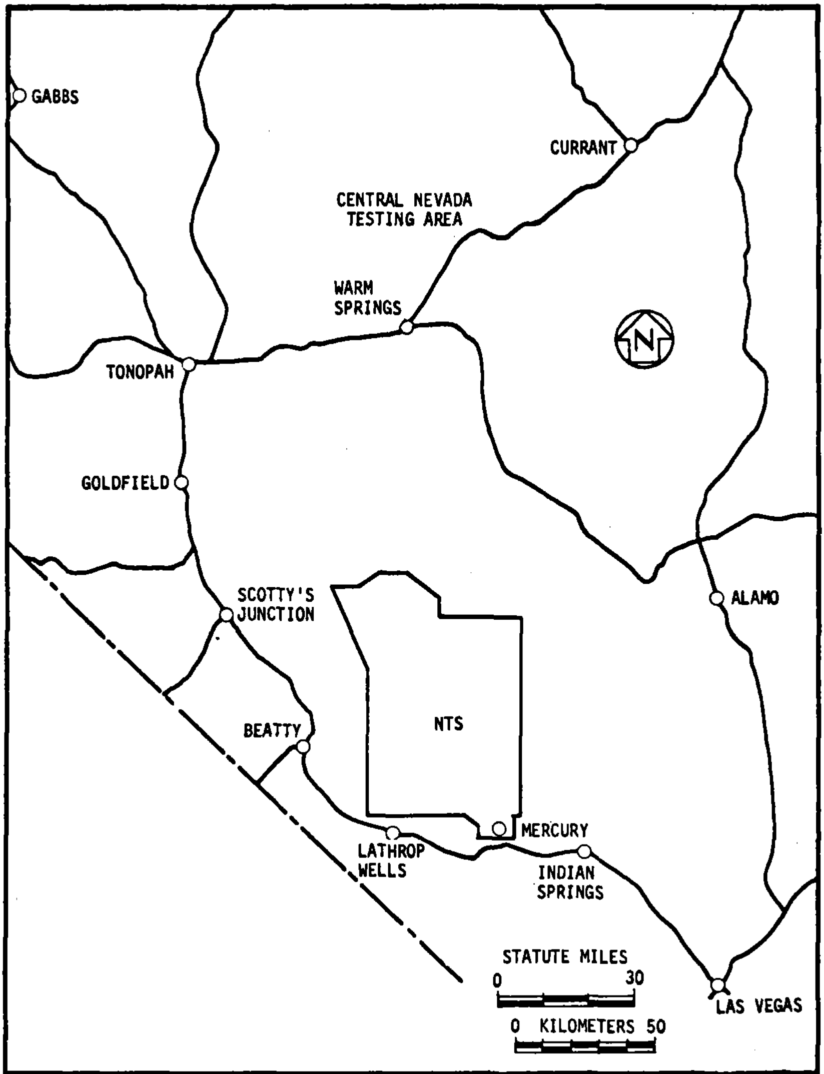

FIGURE 1 NEVADA TEST SITES AND BORDER COMMUNITIES

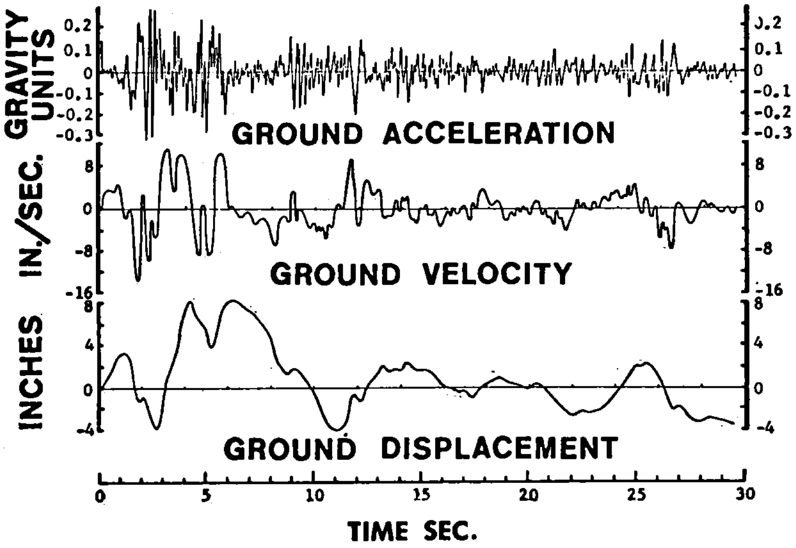

FIGURE 2 1940 EARTHQUAKE AT EL CENTRO, CALIFORNIA; NORTH TO SOUTH COMPONENT

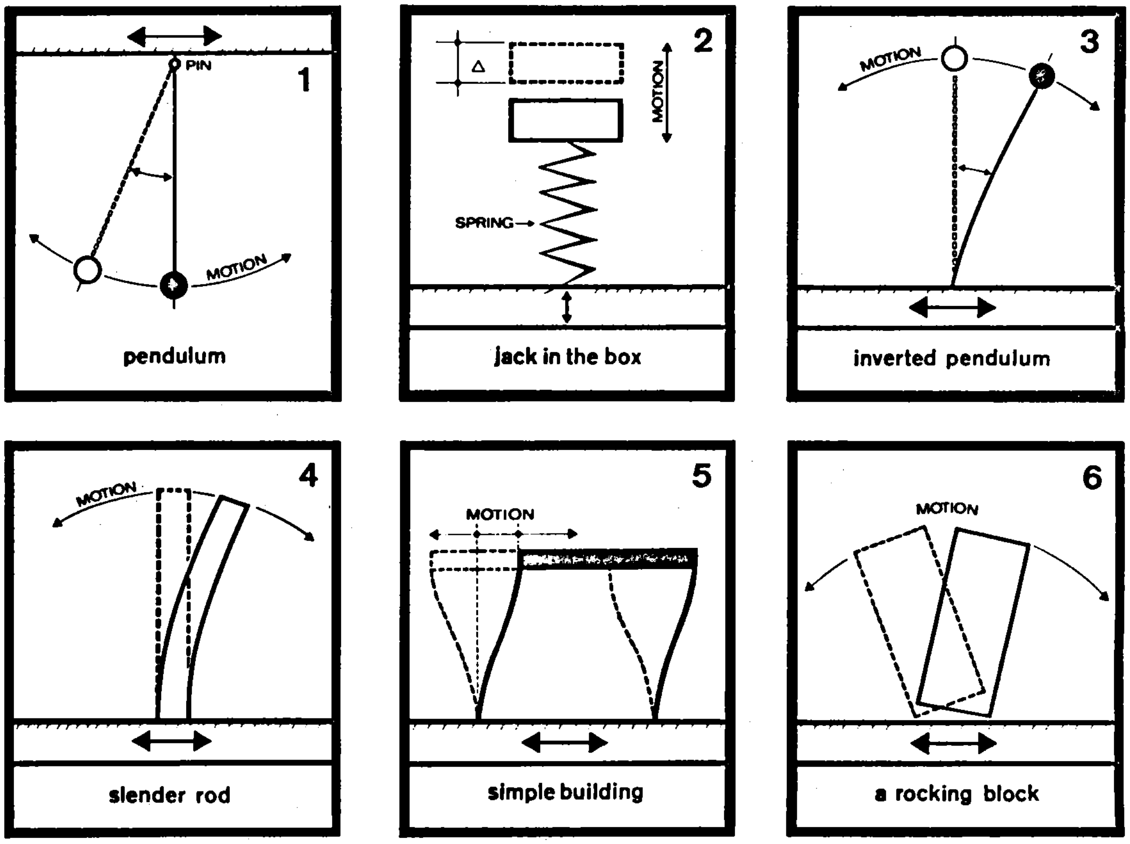

FIGURE 3 IDEALIZED VIBRATING SYSTEMS

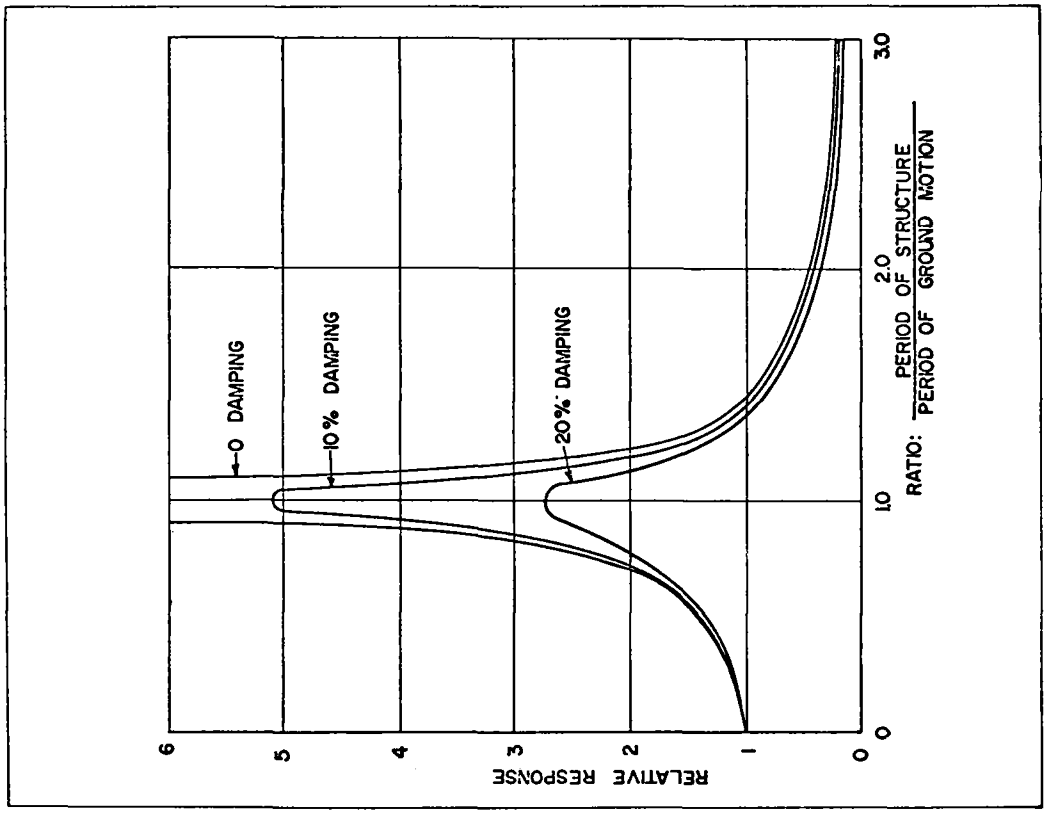

FIGURE 4 RESPONSE TO HARMONIC MOTION

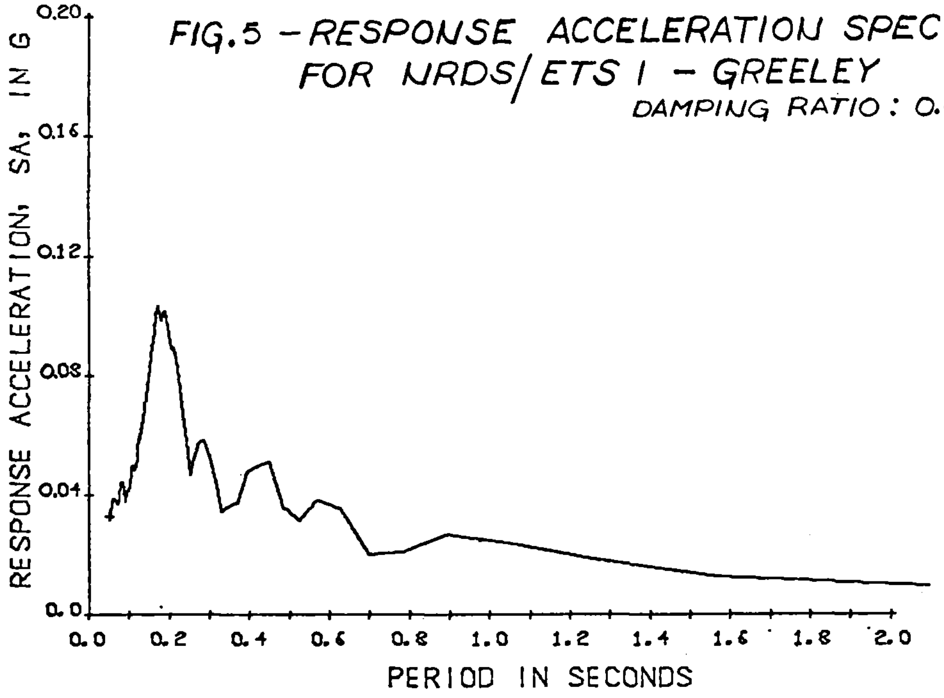

FIG.5 - RESPONSE ACCELERATION SPECTRUM FOR NRDS/ETS I - GREELEY
DAMPING RATIO: 0.05

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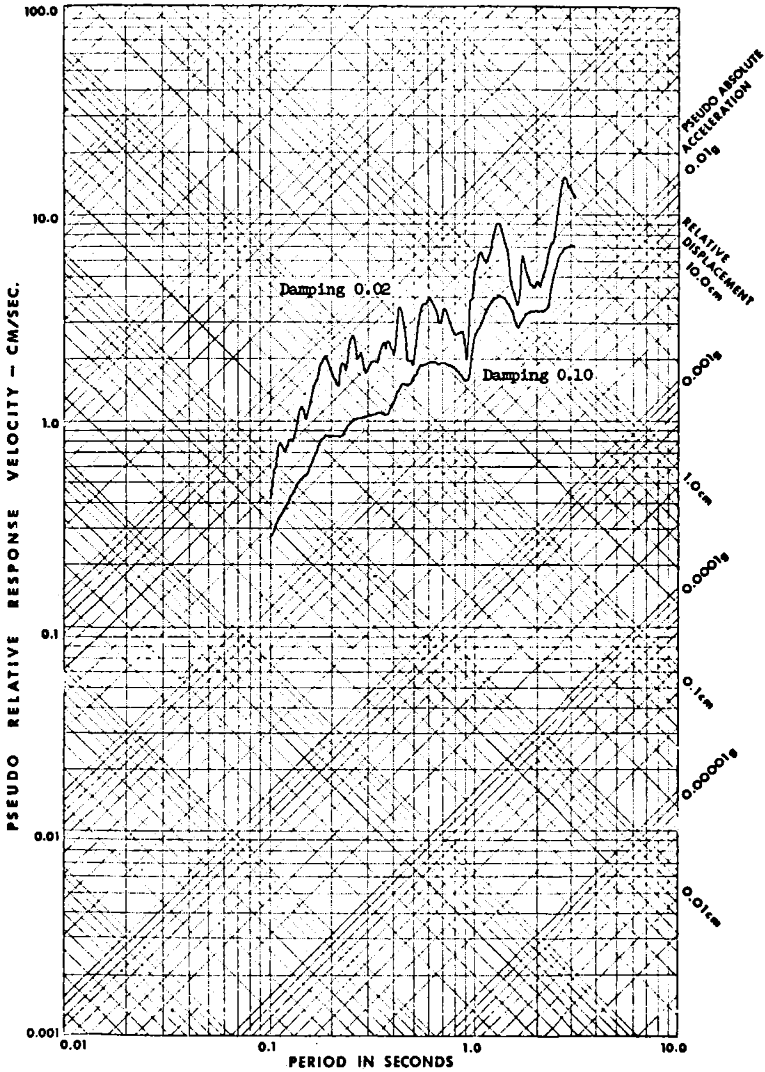


DAMPING 0.02, 0.10 GREELEY NRDS/E-MAD (RADIAL) 6

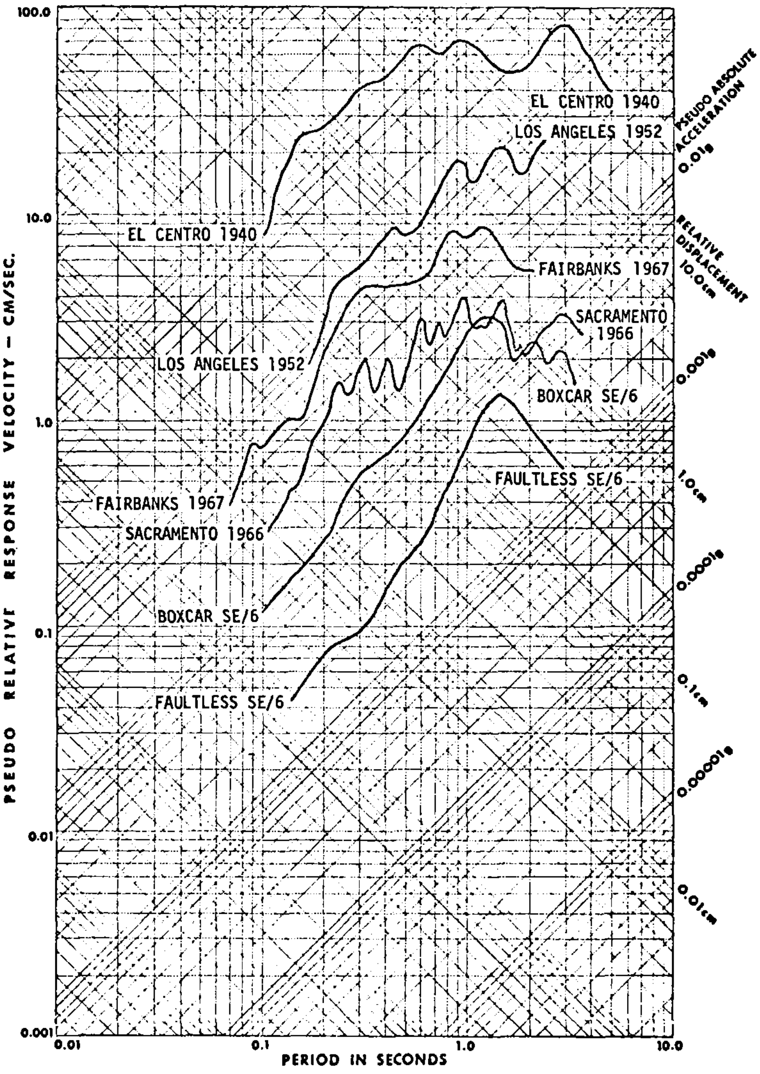
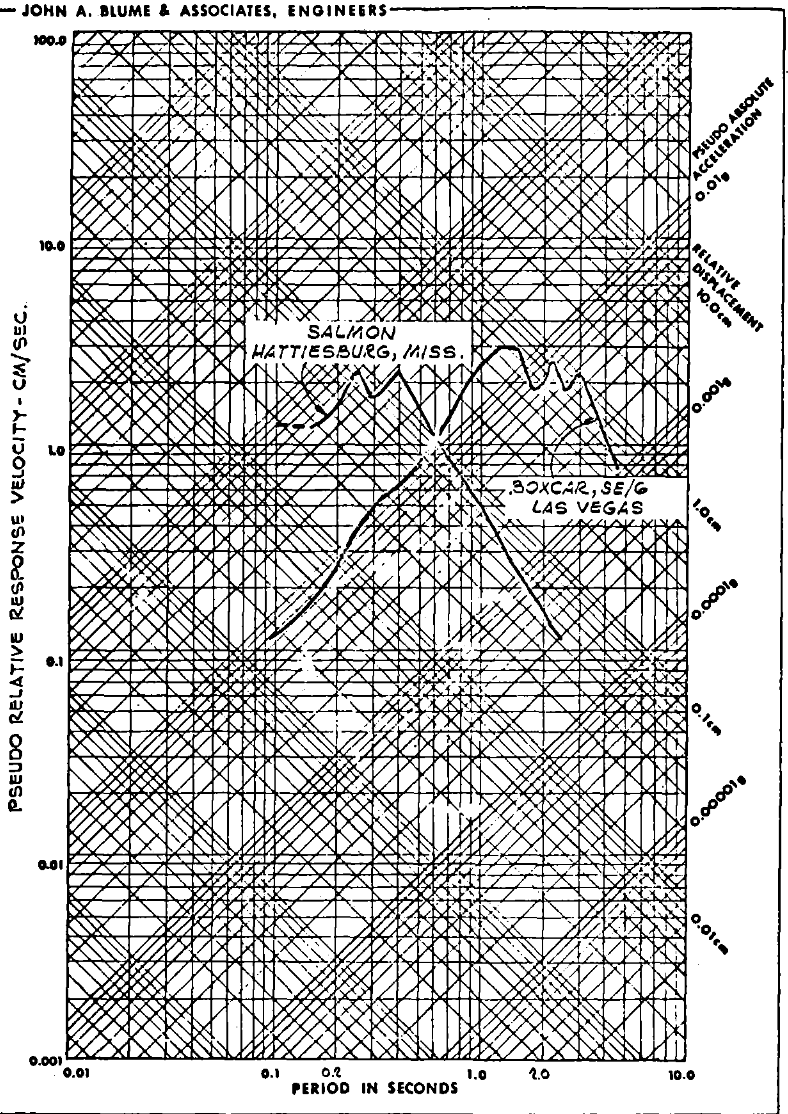


FIG. 7 RESPONSE SPECTRA 5 PERCENT DAMPING



5% RESPONSE SPECTRA

FIG. 8

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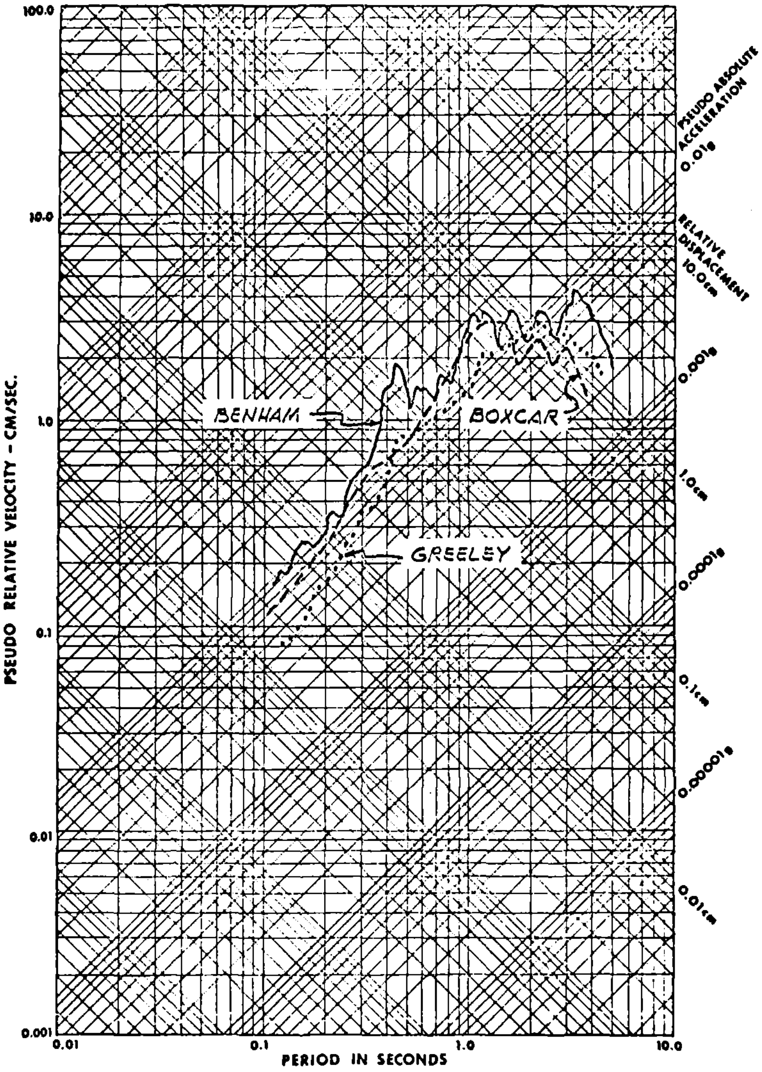

5% RESPONSE SPECTRA, LAS VEGAS, SEG, N-S. FIG. 9

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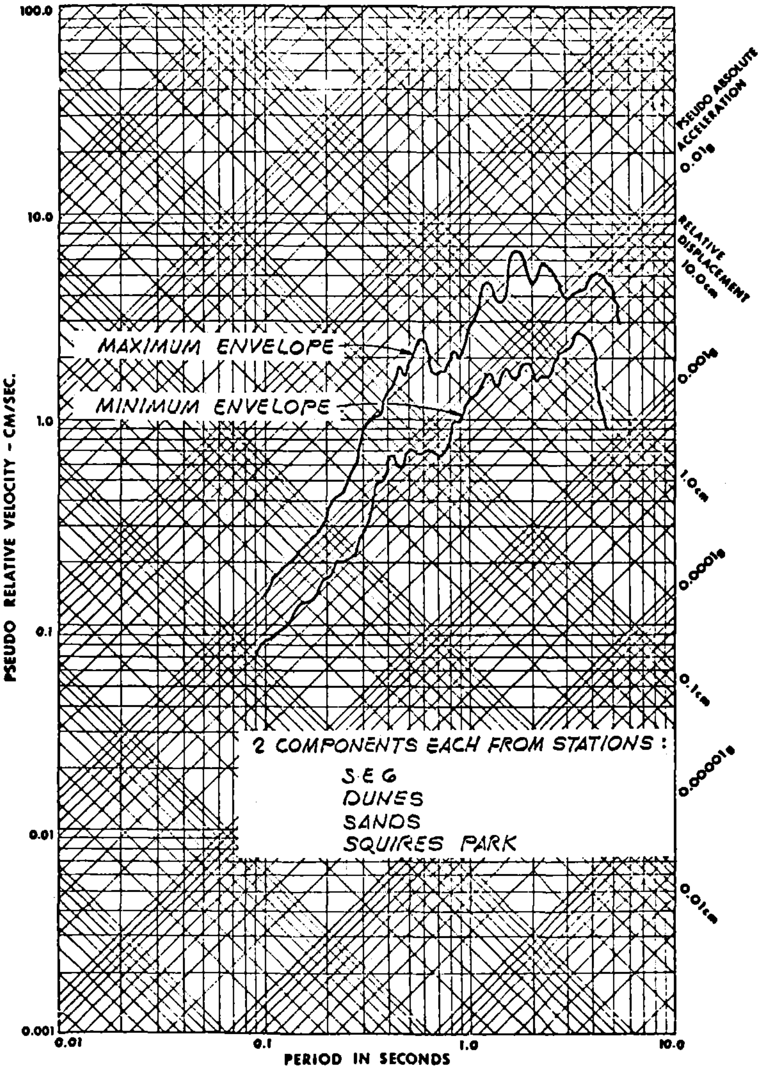


5% RESPONSE SPECTRA, LAS VEGAS, EVENT BENHAM FIG. 10.

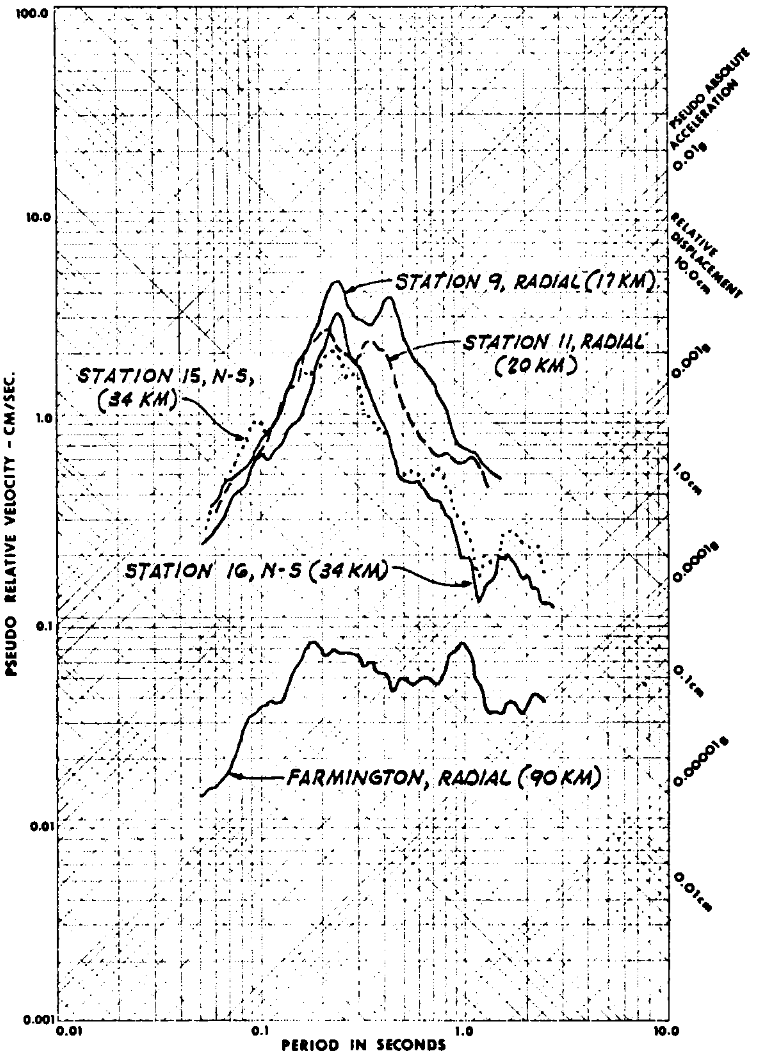
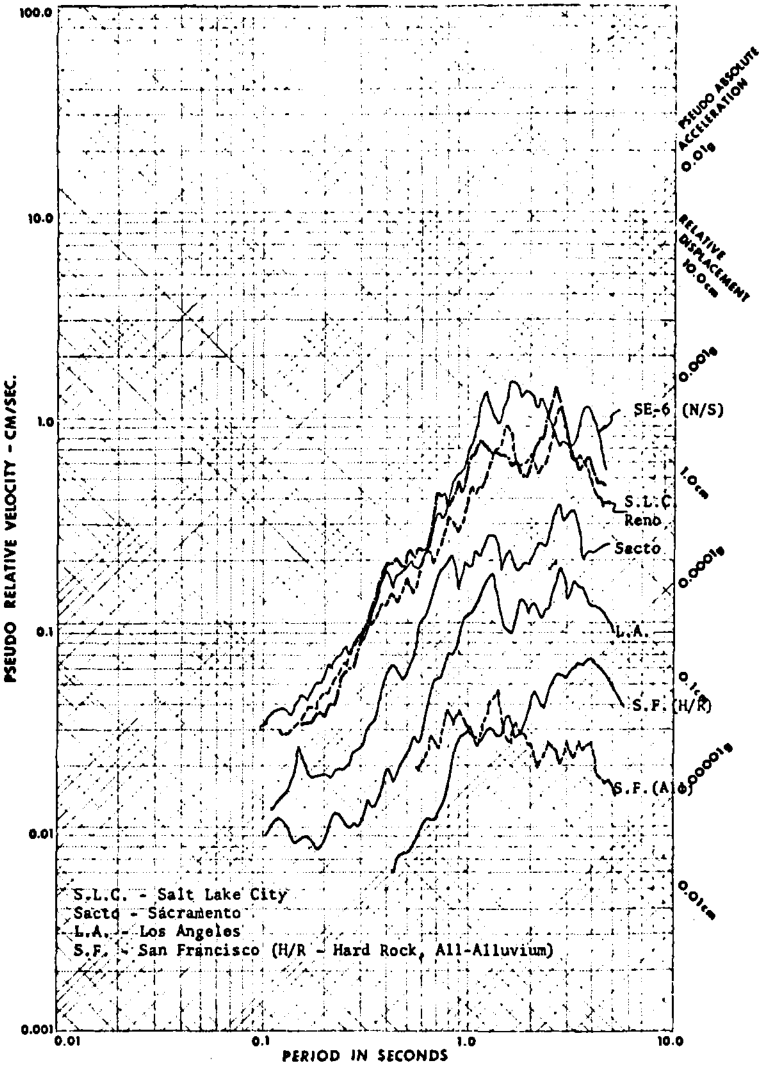
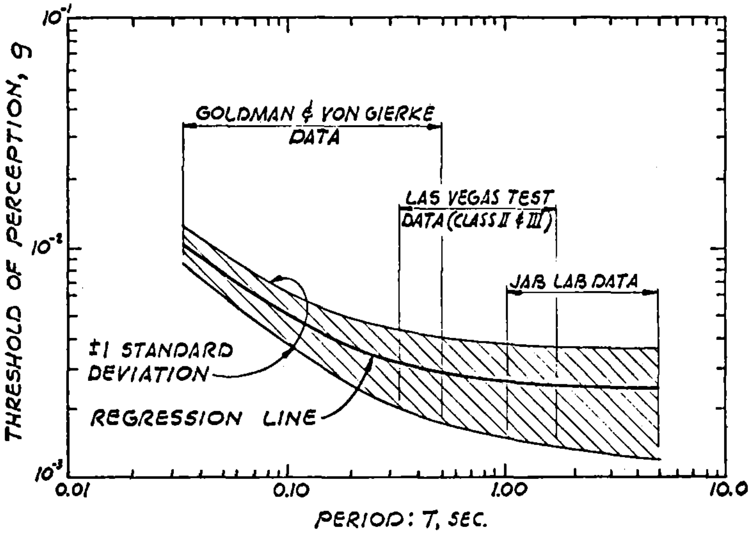


FIG. 11 - PROJECT GASBUGGY, 10% SPECTRA



Damping 0.05	FAULTLESS	Response Spectra Comparison of Major Cities (Radial Component, unless otherwise noted)	Fig 12



REGRESSION LINE: PERCEPTION $= 0.00245 + 0.00025\left(\frac{1}{T}\right)$
STANDARD DEVIATION OF LINE: $\sqrt{S^2} = \pm 0.0012$

FIG. 13: PERIOD VS. ACCELERATION AT THRESHOLD OF PERCEPTION.
DATA OBTAINED FROM LAB TESTS, LAS VEGAS FIELD TESTS, AND FIG. 6.

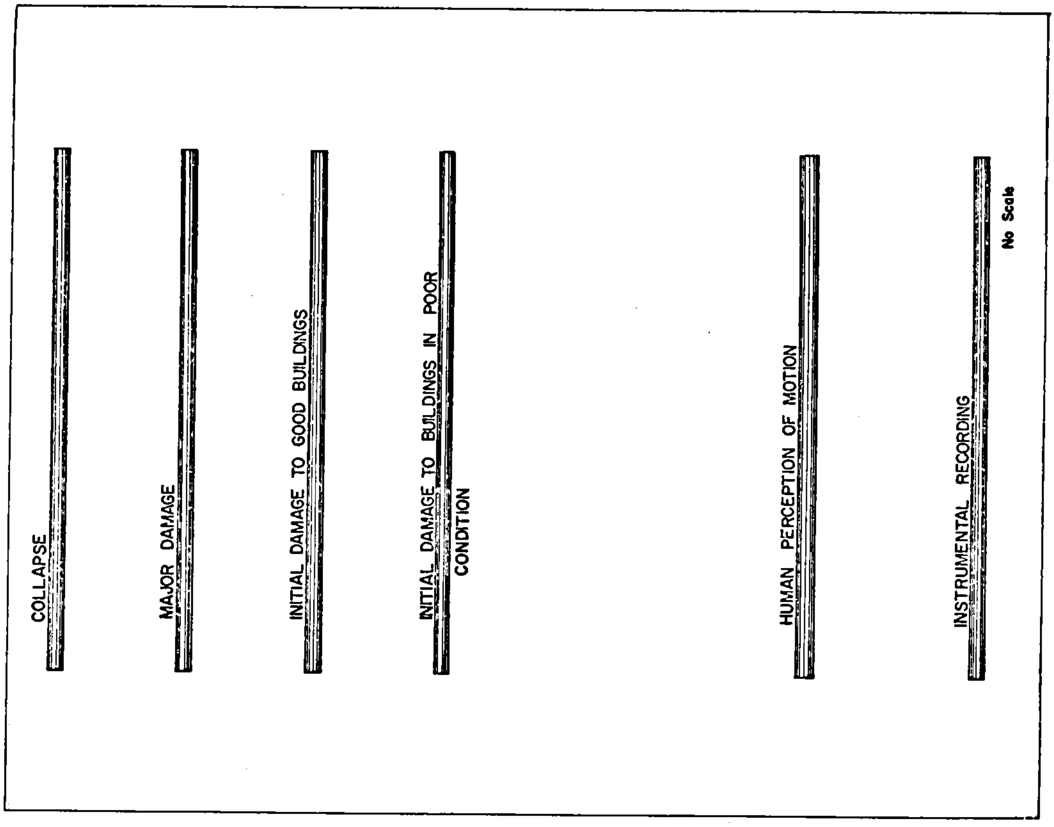
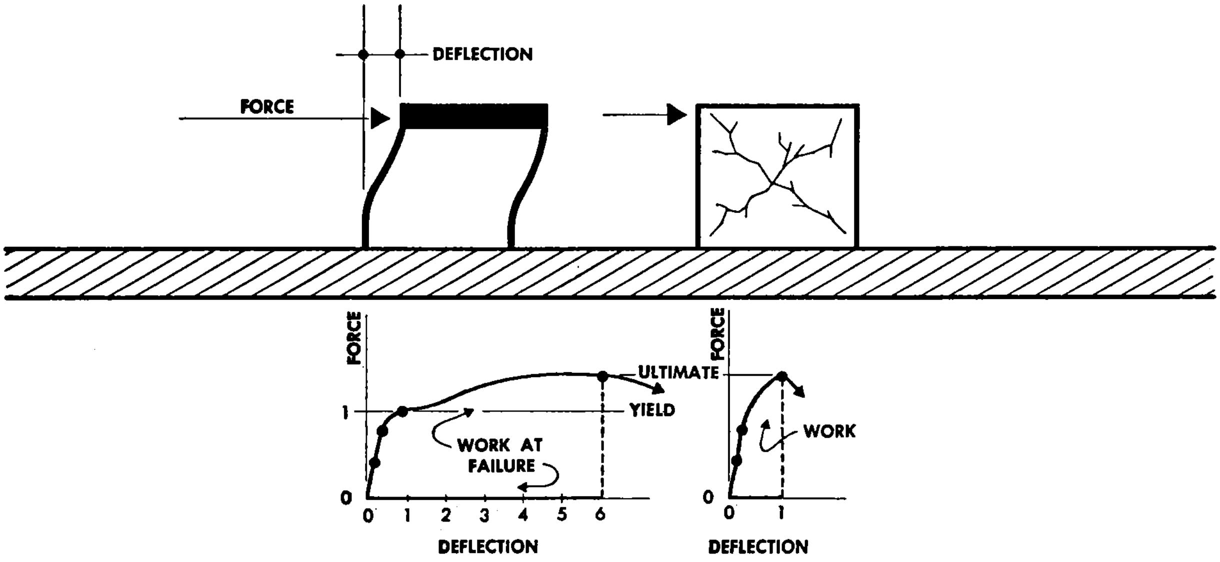


FIGURE 14 THRESHOLD LADDER

BUILDING MATERIAL CHARACTERISTICS



(a) ductile (b) brittle

FIGURE 15

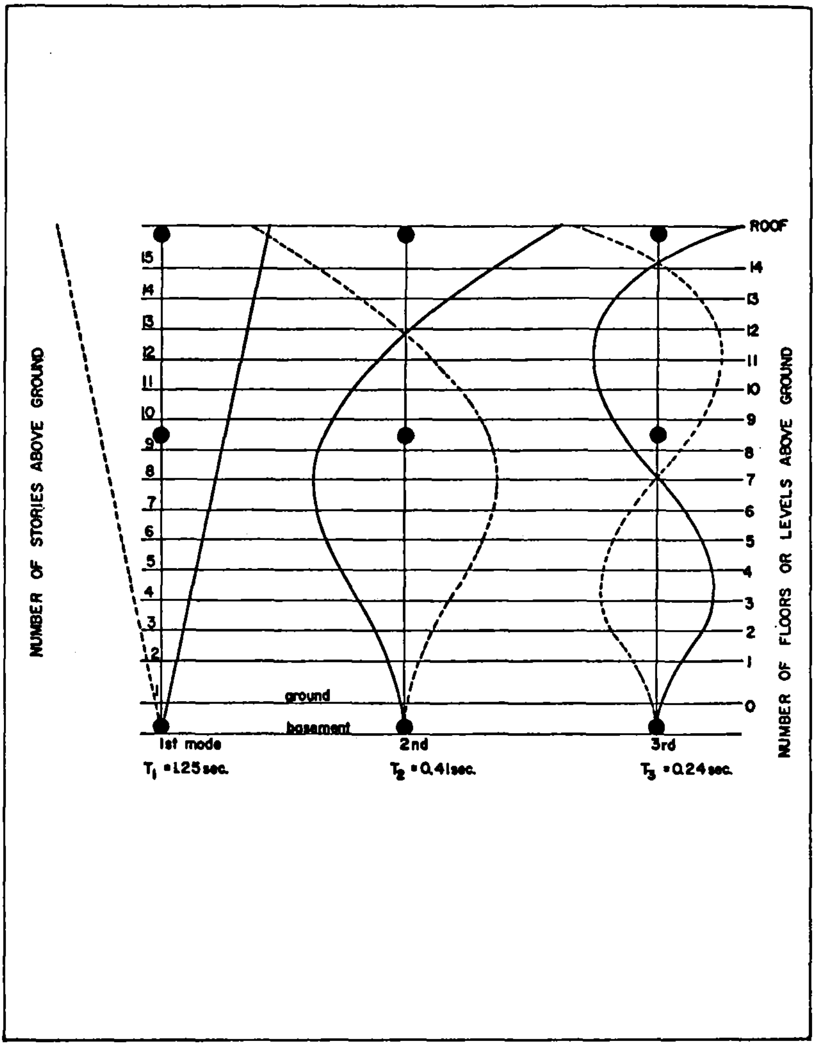
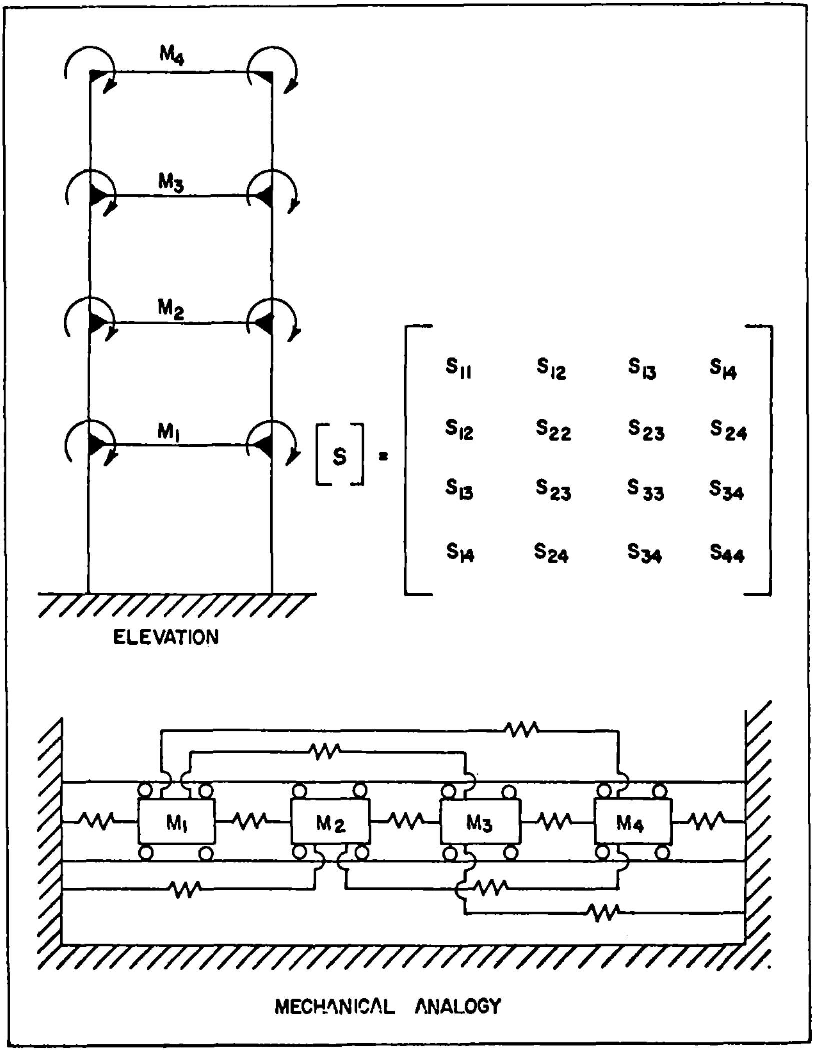


FIGURE 16 Mode Shapes of a 15-story Building.



$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{23} & S_{24} \\ S_{13} & S_{23} & S_{33} & S_{34} \\ S_{14} & S_{24} & S_{34} & S_{44} \end{bmatrix}$$

FIGURE 17 A Far Coupled System.

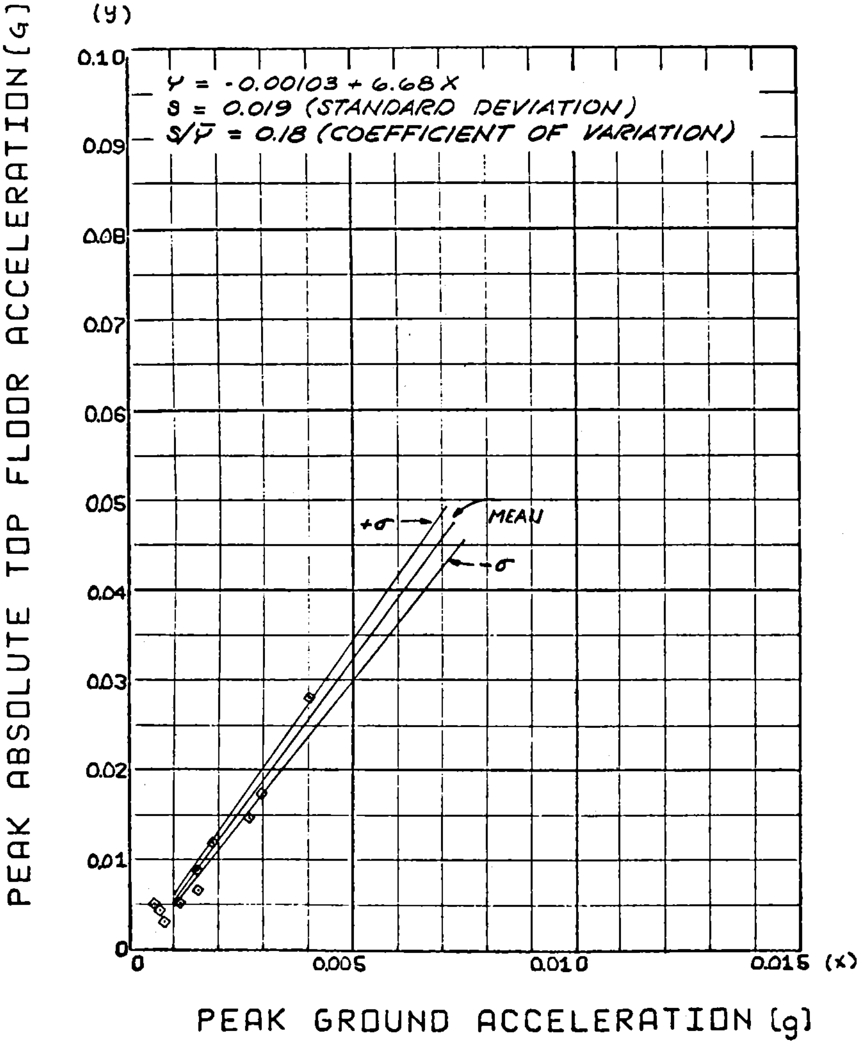
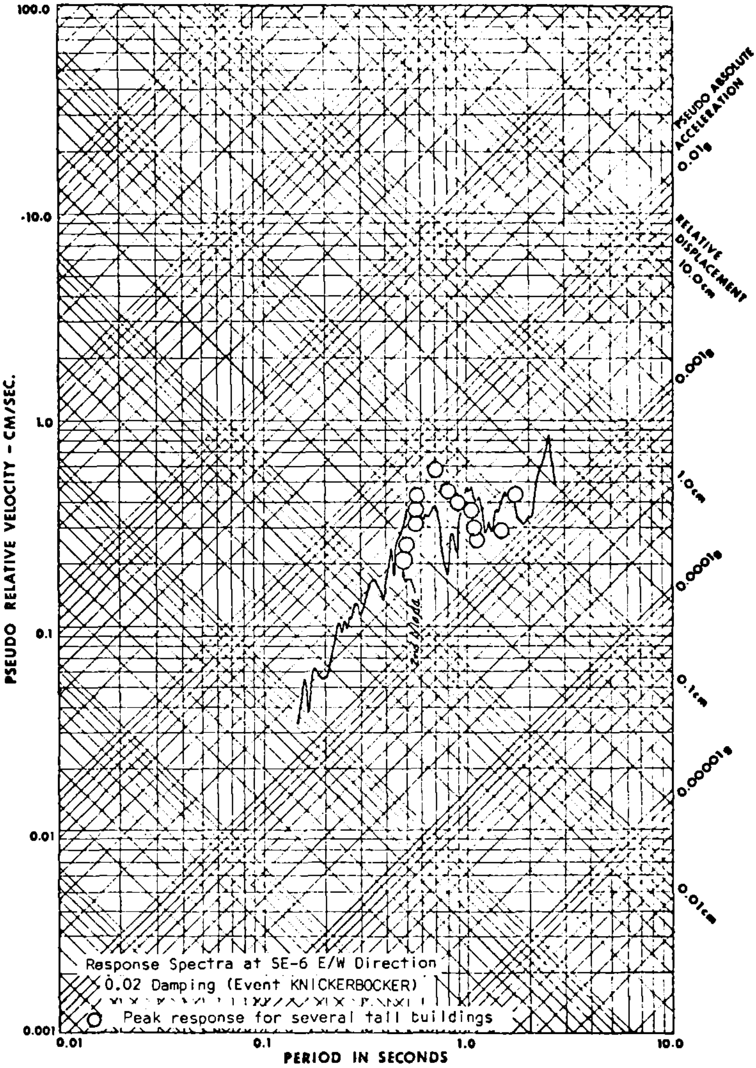
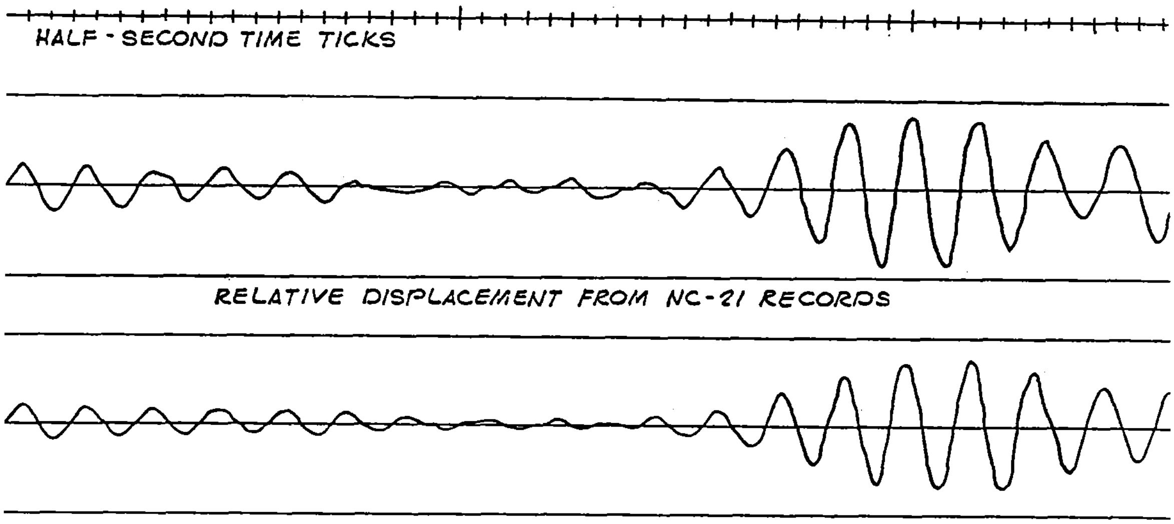

(y)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Y = -0.00103 + 6.68 X
S = 0.019 (STANDARD DEVIATION)
S/$\bar{Y}$ = 0.18 (COEFFICIENT OF VARIATION)
+σ
MEAN
-σ
0
0.005
0.010
0.015
(x)
PEAK ABSOLUTE TOP FLOOR ACCELERATION (G)
PEAK GROUND ACCELERATION (g)

FIG. 18



Recorded Maximum Structural Response vs Period of Mode in Which Response Occurred. Event KNICKERBOCKER (fundamental mode unless otherwise noted).

Fig 19



RELATIVE DISPLACEMENT FROM COMPUTATIONS

FIG. 20 - COMPARISON OF ACTUAL AND COMPUTED RELATIVE DISPLACEMENT, TOP FLOOR, BUILDING A, DUMONT EVENT.

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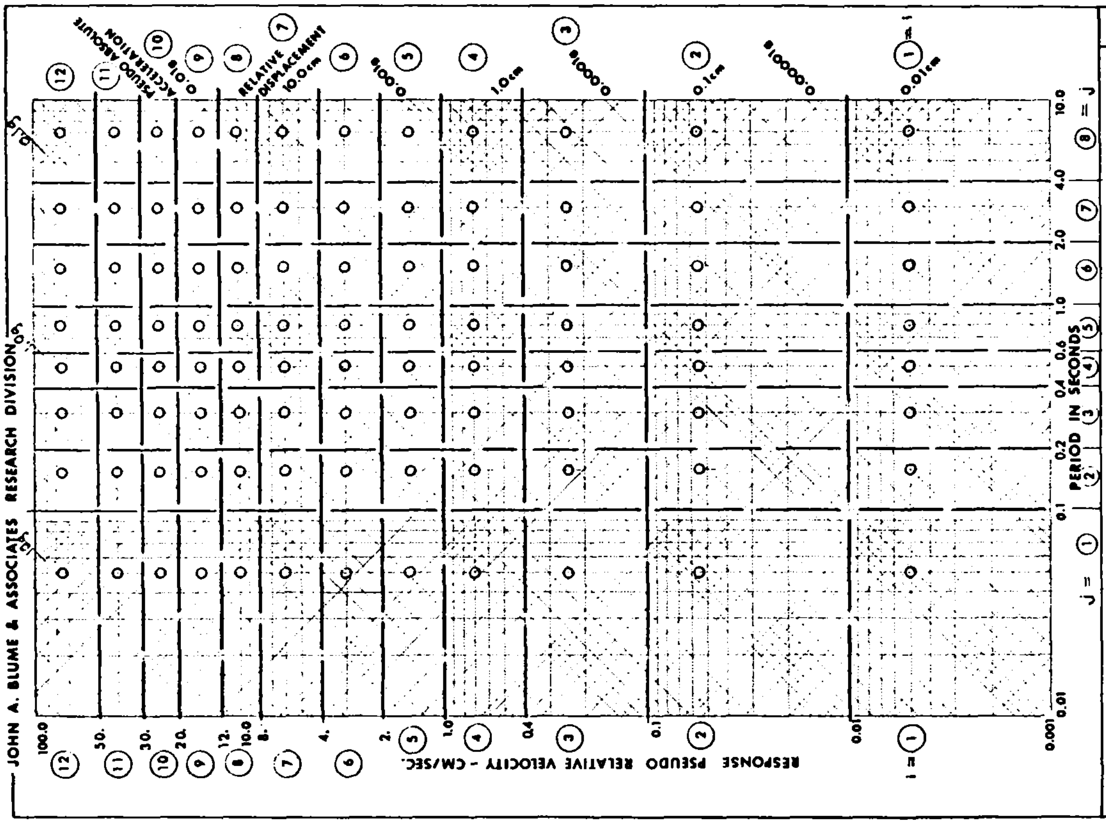

FIGURE 21 - THE SPECTRAL MATRIX SYSTEM

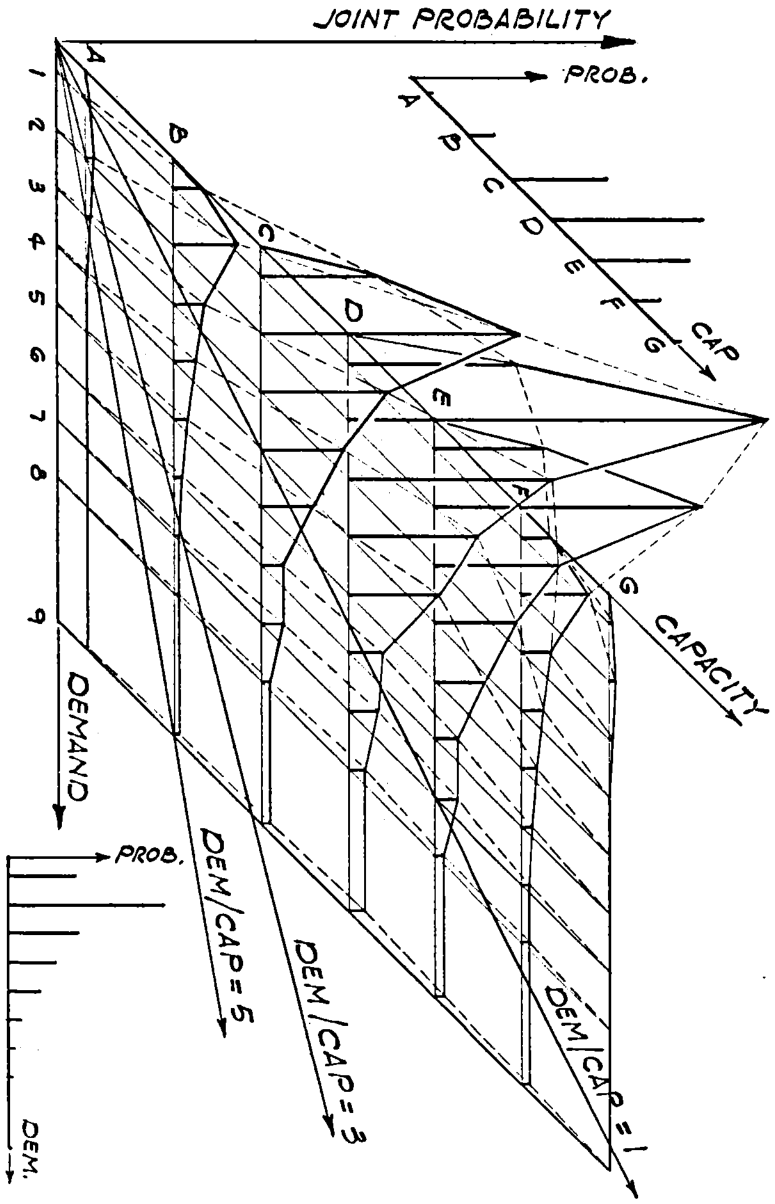

FIG. 22 — SCHEMATIC DIAGRAM OF JOINT PROBABILITY

QUESTIONS FOR JOHN BLUME

1. From R. L. Long:

Is there any way to experimentally determine the resonant frequencies of various building types before an event?

ANSWER:

Yes, there are several ways. The most of which we employ. One of the simplest and most old fashioned methods is simply to go up into a tall building on a windy day and get good records and analyze these very carefully to avoid gust factors to make sure you are getting the building in its natural swing. The limitation of this is that it only brings out the fundamental mode and you're still guessing as to the higher modes, so the next thing is to run a pull test if this is possible and we do this on test structures, but not on private buildings. We simply pull the building over with a wire and a rigging; snap the wire, let it vibrate and record what happens. The third method is by force vibration using machines to actually induce the type of response needed. We do this also, in fact we have a small machine for this purpose, but the problem is that it is very difficult to go into an occupied private building, and to say you want to cut their floor up and to hook a machine into it. They just don't like it.

2. From Walt Kozlowski:

What is your opinion of the structural integrity of the buildings in the Las Vegas area with respect to earthquakes and with respect to nuclear tests?

ANSWER:

First of all, let me say that Las Vegas operates under Zone I of the Uniform Building Code. Zone I means that it has very low seismic design coefficients. To give you another example, Salt Lake City operates under Zone 2 with double the design coefficients and Reno in Zone 3 with four times the design coefficients. Now the difference is not entirely that much, however, because the wind design may possibly govern over the seismic design. What usually happens in any tall building in the low seismic zone, however, is that wind will usually govern the design and means that you have a pretty strong building on the broadside in the motion that is transverse and a rather weak building in the longitudinal direction because they didn't put much wind on the end of the building when they designed it. So I would say that, like most cities, perhaps even a little more so, Las Vegas could have some earthquake problems. For example, the El Centro, California earthquake of 1940 if it occurred again or the Kern County, California earthquake of 1952, in my opinion would make the tall buildings here respond. Whether or not there would be damage, I don't know. The more they respond the more chance of damage. Now why didn't this happen in 1952? There were no high-rise buildings then. The situation with regards to nuclear events is that we just don't dare do much damage to buildings. We don't want to do any if we can avoid it. So they are all being watched very, very carefully. We are using them all as guinea pigs. In fact, I think a great deal of information will come out of this program that will be very, very useful in a natural earthquake field.

3. From Jack Reed:

   What would be the natural frequency of the new forty-story buildings in Bogota and what yield would give peak motions at that frequency?

   ANSWER:

   A forty-story building, if it's a modern type building without many filler walls such as we used to have, could have a natural fundamental period on the order of 3 to 5 seconds, possibly even longer. However, in South America they design a frame and then come in later and put in tile walls so the frame can't act as it was designed. The result is that the period is shortened, the building is stiffened and the tile walls will tend to act as structural members when the ground shock first comes along. This is unfortunate. It is not exclusively South America. We have a lot of these in the United States and some right in Las Vegas. The yield which would get out there is a little bit beyond my normal scope except to say that it would take very, very heavy yields and long distances combined to peak at this period. My guess is that we are probably talking 10 or 20 megatons at that great distance.

Remarks of Rep. Craig Hosmer
Joint Committee on Atomic Energy
Symposium on the Public Health Aspects
of Peaceful Nuclear Explosives
April 8, 1969, Las Vegas, Nevada

PLOWSHARE, POLITICS AND THE PUBLIC INTEREST (BANQUET ADDRESS)

As a friend and strong supporter of the Plowshare Program, I am delighted at the opportunity to come here this evening to speak on its behalf. This is a very important meeting on a tremendously interesting subject. It is especially timely for a variety of reasons.

First, the Senate's recent ratification of the Non-Proliferation Treaty will have a positive, long-term impact on world-wide interest in applications of peaceful nuclear explosives. Article V of the Treaty deals specifically with this subject. The United States, as a nuclear weapons nation, promises to make the benefits of Plowshare available to the non-weapons countries on a non-discriminatory basis.

Second, President Nixon has indicated he intends to pursue the Plowshare program vigorously. A positive indication of this was his instruction to AEC Chairman Glenn Seaborg regarding a feasibility study of blasting a harbor at Cape Keraudren in Australia. The project collapsed, but for totally non-nuclear reasons. Sentinel Mining Company withdrew its interest because it couldn't make a sale to the Japanese of the iron ore to be shipped from Keraudren. But Cape Hedland and Cape Preston are emerging as alternate sites for alternate companies. An Australian Plowshare harbor is still a real possibility. You will be hearing about it quite soon. My lips are sealed for now.

Third, The Joint Committee on Atomic Energy will resume hearings shortly on the Commercial Plowshare Services Bill. As you will recall, preliminary hearings were held on it last year, and I think the committee will broaden its view and look into several related issues this year. I am confident that passage of this bill and the information developed during the hearings will have positive effects on the pace of events in this field.

In short, we are approaching a period of greatly accelerated progress in Plowshare if certain obstacles are overcome. This symposium will contribute information, particularly in the public health area, which is a prerequisite to a broad commercial program. In addition, I would hope that any new questions raised here and left unanswered can be tackled by the Joint Committee at its hearing.

PROMISE OF THE PLOWSHARE PROGRAM

It is interesting to me that the papers being presented and the topics being covered at this meeting are similar to those at another seminar about 12 years ago. That, too, was an historic meeting for Plowshare.

In 1956, one of the periodic Middle East uprisings blocked off the Suez Canal to international shipping. With the patterns of international trade disrupted, serious thought began to focus on alternatives to and substitutes for the Suez Canal. Creative minds at the Lawrence Radiation Laboratory came up with one of the better ideas: namely, if you can't get through the existing canal, dig a new one! And do it with nuclear explosives.

A year later, in 1957, the year in which the first underground shot was ever fired, a "brainstorming" symposium was organized at LRL to examine the concept of peaceful nuclear explosives. The program still had no name and very little money, but the scientists were certain they were on to something important. Sometime later, I don't recall when, Edward Teller succeeded in attaching the Plowshare name to it.

Unlike today's symposium, the earlier one was cloaked in a necessary shroud of secrecy and security.

The now declassified papers of 1957 demonstrate the remarkable clarity of foresight possessed by these Plowshare pioneers. With very few exceptions, their message was economics--how to introduce peaceful nuclear explosives into the marketplace at costs competitive with conventional industrial processes and technology.

All three categories for possible use were mentioned--excavation technology to build canals, harbors, or knock down geologic obstacles; underground engineering for petroleum production, gas stimulation, and mining; and scientific applications for seismic studies, neutron sources and new element production. With essentially zero experience in below-surface explosions of nuclear size, the participants recognized the key technical problem areas--radioactivity, containment and ground motion.

SOME OBSTACLES TO BE CLEARED

Today, at this meeting, we are seeing where we have come and how far we still have to go. For a variety of reasons, we have not moved ahead in this field as fast as we might have. When you compare progress in reactor development with that in Plowshare since, say, 1960, I think it is clear that Plowshare has been dragging.

There are understandable historical reasons for this. In the first place, Plowshare was, and to a large degree still is, a government reserve. Industry, the potential user, was not brought in at the beginning. Only in recent years have we seen the development of private industrial interest in specific applications. Meanwhile, classification, parental jealousy and over-protectiveness--all human frailties--have played their delaying roles.

Nor for the first decade and a half of the nuclear age was industry particularly alert to Plowshare opportunities. In 1958, for example, it rejected out-of-hand a joint AEC-Bureau of Mines proposal to detonate a Plowshare explosion in the oil shale of Colorado. The oil companies found a variety of superficial flaws in the project, without examining either its underlying concepts or its potentials. Later, of course, the nuclear test moratorium slowed Plowshare to a crawl and hindered establishing a rapport between government and the private sector. But that is past history. There is a healthy interest now.

Probably the most exasperating obstacles to progress in this area have been and still are those so-called "liberals" whose conscience pangs cause them to view any peaceful application of atomic energy in terms of a mushroom cloud. It strikes me as irrational that these people are offended by attempts to develop the power of the atom for man's benefit. They are 100% for foreign aid and the Peace Corps, but 100% against foreign Plowshare applications and 200% against domestic ones. To hear them tell it, Plowshare, by itself, is the single major obstacle to total and complete world disarmament.

In addition to the assorted professors, scientists, lawyers and literati who whine over Plowshare for philosophical reasons, a hard core of Plowshare opponents seems to have developed within the Executive Branch of the government itself--particularly within the Budget Bureau, the State Department and the Arms Control and Disarmament Agency. Behind the scenes, this group strenuously fights to obstruct every attempt at upgrading the program. These people seem to have a paranoiac distrust and abhorrence for Plowshare, which they cannot divorce in their minds from the weapons program. I am sure Article V of the NPT, which gives Plowshare international respectability, must have broken their bleeding hearts.

Despite the fact that this program generally has strong support within Congress, industry, the AEC and in most corners of the Executive Branch, this clique exercises considerable clout in opposing it, by budget constriction and otherwise. For example, in early 1967, the Cabriolet experiment was summarily cancelled by the Johnson Administration for fear of upsetting negotiations on the NPT and the Latin American Treaty on a Nuclear Free Zone. At that time, I made a speech in the House of Representatives questioning the judgment that led to this decision. It is totally beyond me how a research program aimed at developing the peaceful atom could be construed as detrimental to efforts at halting the spread of nuclear weapons.

Another more recent example concerns the late, lamented Cape Keraudren project. The AEC was directed by the President to actively and promptly study the feasibility of the project. Yet this same anonymous brotherhood seemed to do everything within its power to prevent the Commission from getting any money, even for the feasibility study.

Since the Limited Test Ban Treaty was signed in 1964, they have never ceased forwarding overly-legalistic interpretations calculated to eliminate the possibility of Plowshare excavations. The Treaty prohibits a nation from "causing to be present outside its national boundaries" radioactivity from a nuclear explosive device, warlike or peaceful. They claim one single radioactive atom beyond the three-mile limit would constitute a violation. Yet all of our standard radiation protection guides--even those adopted by the United Nations--state that radiation is "not present" when its measurable amount constitutes less than 10% of the established maximum permissible concentration. Further, these guides relate to human exposure, not merely to abstract presence.

Based on evidence which admittedly is somewhat tenuous, my own belief is that the Soviets are anxious to remove the handcuffs of the Limited Test Ban Treaty from nuclear excavations. They have plenty of geological cosmetology which is in their self interest to perform, just as we do. Since any treaty means precisely what the two most powerful signatory nations say it means, I am of the opinion that the LTB can be rapidly brought into line with the facts-of-peaceful-nuclear explosions-life, if certain people in our own government will stop throwing up artificial hurdles.

WHAT WE HOPE TO DO THROUGH H. R. 477

It is accurate to say that without the continuing support of the Joint Committee, the Plowshare program might have been successfully sidetracked, eventually buried, and never heard of either domestically or on the international scene in the form of the NPT's Article V provisions. We may not be able to overcome all the anti-Plowshare forces in the government, but we are going to try to get Plowshare off the back burner by enacting H.R. 477, the Commercial Plowshare Services Bill. This Bill is co-sponsored by all the House members of the Joint Committee, and a Senate companion with similar bi-partisan support is expected shortly.

Under present law the Atomic Energy Commission is essentially confined to experiments involving research and development. Our objective is to give the AEC authority to make Plowshare services available on a commercial basis. Since, under terms of the Non-Proliferation Treaty, the United States has an obligation to provide commercial services to non-nuclear nations, the new legislation is sufficiently comprehensive to accommodate foreign as well as domestic customers.

PLOWSHARE--A BUSINESS

As AEC gears up to furnish commercial Plowshare services, there are a number of business decisions and businesslike procedures which need to be concluded. There are still, of course, technical areas needing additional R&D--which is your job. But some of the procedural and policy issues before us in government also need resolving:

First, exactly what the government is to furnish under the category of "peaceful nuclear explosive services" must be defined, and the responsibilities of the customer and his engineering consultants must be fixed. Within the government, a management structure must be established to coordinate and control the various inputs which will be made by AEC, the Public Health Service, the Interior Department and other appropriate government agencies.

Second, a standard line of devices must be established, perhaps 12 to 18 in number, providing a reasonable combination of yields and other characteristics. After this initial R&D effort, it will be impossible to tailor each shot minutely to a customer's particular requirements. The government cannot be expected to involve itself in new

R&D expenses every time another customer comes along. The Non-Proliferation Treaty requires that the charge for services to foreign customers exclude R&D cost and that the services be supplied on a non-discriminatory basis between all customers. Since this makes R&D expenses unrecoverable, the only way they can be minimized is by the standardization technique.

Third, a price list must be posted which the NPT requires to be "reasonable" and which, in any event, is necessary if potential customers are to know enough about their costs to make rational decisions.

Fourth, in the case of foreign customers, we must reexamine our agreements for cooperation, under which U.S. and other nations spell out the extent of their nuclear collaboration to make sure that special requirements as to Plowshare are covered. I have in mind such things as retention of the devices under U.S. custody and control, public health and safety responsibilities, liability questions, compliance with the Limited Test Ban Treaty and the NPT and similar topics requiring orderly separation of responsibilities.

Fifth, in the case of domestic customers, we shall have to establish regulatory control measures not unlike those that apply to nuclear power reactors and resolve jurisdictional questions between federal, state and local governments.

REGULATION AND CONTROL

This area of regulation and control is as important to the formation of an industry as price, technology or any other factor. I foresee the AEC as the executive agent for the government for this purpose. In addition to developing the devices and furnishing the explosives services, AEC's role is likely to include the following:

--Absolute control of nuclear explosives until their detonation.

--Protection of the public from harm caused by radioactivity or seismic damage at the time of detonation.

--Protection of the public from harm caused by radioactivity present in any commercial product resulting from a nuclear explosion.

--Protection from physical damage to buildings or structures.

In assuming this regulatory role, the AEC should be cognizant of several characteristics of the industries most likely to be involved in commercial applications of nuclear explosives. Industries such as natural gas are already highly regulated. The FPC strictly controls the gas pipeline industry. It typically requires two years to process an application for development of new gas fields, connections to existing pipelines, construction of new pipelines and establishment of the rate structure for gas from such a field.

Other agencies are involved in the safety aspects of pipeline construction and operation. The recent Santa Barbara Channel blowout bears witness to the government's present multi-agency involvement in environmental pollution, and points to an ever expanding governmental role in safety and pollution aspects of industry.

The point to be made here is that the AEC should recognize that it is moving into an area already strongly controlled by government, and that only those additional controls necessary under the Atomic Energy Act need be instituted. Its function as to existing controls should be that of a coordinator in these peripheral areas.

A possible scenario of the AEC's Plowshare regulatory role could go like this: The industrial applicant would be required to submit a detailed proposal for the project including the equivalent of a reactor safety analysis report which evaluates in detail radioactive and seismic safety at the time of detonation as well as possible product radiological contamination. The AEC would then conduct a detailed review of the proposed project in the same way reactor applications are reviewed. This review would be in parallel with other government regulatory reviews so that the already excessive regulatory times are not further extended by the AEC process. Assuming AEC approval of the application, provision probably should be made for a public hearing. Our options are either to provide a mandatory hearing in all cases, or just on request from affected members of the public.

Once the project has been approved, the AEC and the licensee would negotiate a contract covering the detonation services, explosives and arrangements for adequate insurance coverage. Preceding the detonation itself, the AEC would have to perform or coordinate inspections from the public health and safety standpoint, and assure that all emplacement and stemming procedures have been properly performed. Final legal permission then would be given for detonation. Following the shot, the AEC would be required to retain control of the area as necessary to protect the public health and safety.

The foregoing is not intended as a comprehensive description of the probable Plowshare regulatory picture, but it does indicate the kinds of considerations involved and underlines the fact that large-scale applications of Plowshare technology are going to require carefully designed and intelligently administered procedures.

DIVORCING PLOWSHARE BUSINESS FROM THE WEAPONS EFFORT

At this point I am going to start treading on some toes, in the AEC in general and at the Lawrence Radiation Laboratory in particular. For I do not see how Plowshare can really succeed unless the responsibility for its peaceful explosives devices and their use is divorced from the weapons program, which has an entirely different underlying philosophy.

In Plowshare, the primary emphasis will have to be on economics. In this competitive field, economics is crucial. A Plowshare device does not have to be the most efficient nuclear device ever built. It doesn't have to be the smallest or the lightest. It must be safe and it must be clean. But it does not have to possess the ruggedness, reliability and other characteristics of a warhead. Since it is not a weapon, it will have to be designed, handled and used with the unique requirements of its users in mind. These users are not the Army, Navy and Air Force. They are civilians pursuing their economic enterprises in a cost competitive environment.

From its inception, Plowshare has been a step-child of the weapons program, both at LRL, the Nevada Operations Office and at the Nevada Test Site. Until the recent series of Plowshare tests--Gasbuggy, Cabriolet, Buggy and Schooner--this dependence was desirable, if not absolutely necessary, even though a side effect has been to associate the weapons and Plowshare programs together in the public mind. Now the time has come to separate the two, both in the public mind and as to technical objectives.

LRL, NVOO and NTS from their inception have been dedicated almost exclusively to weapon devices and tests. They are geared up to satisfy one customer--DOD. They have been a very efficient operation for this purpose, and we can be thankful as a nation for that. But they are not geared up, technically or philosophically, to satisfy efficiently the El Paso Natural Gas Company, the Austral Oil Company, the Kennecott Copper Corporation, or other Plowshare customers.

These weapons organizations are so traditionally geared to conducting test programs for military weapon systems that cost is of minor importance. On something as vital to our security as weapons R&D, we can't afford to quibble over a few dollars. But this basic attitude is incompatible with the Plowshare program, where you must quibble over pennies. If they don't develop economic explosives and emplacement methods, the whole purpose of the Plowshare program will become academic because industrial interest will vanish.

The weapons scientists at LRL have an entirely different set of values than does the Plowshare group. Yet during the execution period for any Plowshare event, responsibility is transferred to the weapons people. There is even some evidence that Plowshare is little more than a nuisance to the weapons organizations, and that they conduct Plowshare tests in the same extensive and expensive manner that weapons test procedures dictate.

As an example, the LRL Plowshare engineering group formulated an operational plan for the Cape Keraudren project that involved operating from a ship anchored offshore. Maximum preparation of the explosive would be done at LRL before transportation to Australia by ship. At the site, operational personnel would be housed and fed on board the same ship. The emplacement of the explosives would be done from the ship, utilizing barge-mounted cranes. The vessel would then move to a safe distance, and the row charge of explosives fired by a radio link. This procedure could save $1.5 million over conventional land-based operations with air transportation of the explosives, amounting perhaps to 15% to 20% of the total project cost. But the entire concept was vetoed by the weapons test group for the apparent reason that they simply "don't do things that way."

I don't have any specific recommendations to make in this area tonight, but I think it is something we all can think about--particularly within AEC. And the Joint Committee should devote some careful attention to it during the hearings. We could consider whether the Plowshare program should be transferred to the oversight of another field office, such as San Francisco or Grand Junction. An independent Plowshare group could have complete responsibility for the design and fabrication of explosives, the conduct of experiments, and the conduct of the commercial service itself. It would separate weapons and Plowshare philosophically and politically, and it would assure that the program is responsive to the civilian user's technical and economic requirements.

PLOWSHARE AND PUBLIC RELATIONS

Before I leave you this evening, I would like to say a few words about the public relations aspects of this program. Despite the fact that we will be conducting these events in very remote and unpopulated areas, it still will be necessary to conduct an active PR campaign to demonstrate the benefits to be achieved. I think the unfortunate experience with Project Ketch, where opposition from the public and state officials caused the withdrawal of the application, is an example of the continuing need to emphasize the benefits to society. We found during the early days of the reactor development program that winning public support and defusing the nut-fringe must start early in the project and continue actively. For example, with an underground engineering shot, if we could show convincingly how this type of mining does not deface the surface of the earth, as does strip mining, we might even end up with the Sierra Club on our side.

I don't think it is possible to overemphasize the importance of developing public support for Plowshare. Given a clear, accurate picture of the potential benefits and the high level of scientific precautions being taken, the public will not be unduly alarmed about possible hazards. For its part, industry must do its homework well and promptly respond to public inquiry and hesitation. When this is done, this nation and the world will be able to glean the vast benefits available by applying this new engineering tool to man's advantage instead of his destruction.

SESSION III - PART C

Chairman: Dr. Delbert S. Barth
National Air Pollution Control Administration
Durham

ECOLOGICAL TRANSFER MECHANISMS - TERRESTRIAL*

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ABSTRACT

Radionuclides produced by nuclear excavation detonations and released to the environment may enter a variety of biogeochemical cycles and follow essentially the same transfer pathways as their stable-element counterparts. Estimation of potential internal radiation doses to individuals and/or populations living in or near fallout-contaminated areas requires analysis of the food-chain and other ecological pathways by which radioncùlides released to the environment may be returned to man. A generalized materials transfer diagram, applicable to the forest, agricultural, freshwater and marine ecosystems providing food and water to the indigenous populations of Panama and Colombia in regions that could be affected by nuclear excavation of a sea-level canal between the Atlantic and Pacific Oceans, is presented. Transfer mechanisms effecting the movement of stable elements and radionuclides in terrestrial ecosystems are discussed, and methods used to simulate these processes by menas of mathematical models are described to show how intake values are calculated for different radionuclides in the major ecological pathways leading to man. These data provide a basis for estimating potential internal radiation doses for comparison with the radiation-protection criteria established by recognized authorities; and this, in turn, provides a basis for recommending measures to insure the radiological safety of the nuclear operation plan.

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INTRODUCTION

Some of the proposed peaceful uses of nuclear explosives, which involve nuclear cratering will result in the release of radionuclides to the biosphere. These radionuclides will be redistributed by ecological processes and may be transported to man in the form of contaminated foods and water, thus resulting in his exposure to internal radiation. A thorough evaluation of the public health aspects of these peaceful uses of nuclear explosives will therefore require an evaluation of potential internal radiation doses to man, and this requires an understanding of the ecological transfer mechanisms whereby radionuclides deposited in the biosphere may be returned to man.

During the past four years, the Battelle Memorial Institute-Columbus Laboratories, and various subcontractors have been engaged in a program of ecological studies designed to evaluate the radiological safety feasibility of using nuclear explosives to excavate a sea-level canal between the Atlantic and Pacific Oceans.[1,3] The basic objective of this program is to estimate the potential external and internal radiation doses to people living in or near the areas that would be contaminated by radioactive debris from the proposed nuclear detonations. These estimates can then be used in planning the nuclear operation in such a way that the radiological safety of both project personnel and the general population would be assured.

Estimates of external radiation doses can be made on the basis of source term[4] and fallout[5] predictions, but the models used to calculate potential internal radiaton doses[6] also require estimates of the probable rates of radionuclide ingestion by the people comprising the reference population. These estimates are being provided by mathematical models designed to simulate the ecological redistribution of radionuclides and their transport to man via contaminated foods and water.

In this paper we shall describe some of the general procedures and concepts that have been used in developing ecological models. As implied by the title, the examples used will be based primarily on terrestrial ecosystem studies although the procedures and concepts involved may have a wider application. Since the studies from which these examples are drawn are not finished, emphasis will be on methods instead of results.

Pathways of Radionuclide Transport

Figure 1 is a highly generalized diagram showing some of the major pathways of potential radionuclide transport from the biosphere to man in an area such as eastern Panama and northwestern Colombia. In this area, the subsistence economy of the indigenous population depends primarily upon primitive agriculture, hunting in the forests, and fishing in the freshwater streams and oceans. Virtually all the foods and water comprising the total diet are derived from the immediate environment. Between 65 and 85 percent of the solid foods included in the diets of people now living in the area is derived from the terrestrial environment, i.e., from the forest and agricultural ecosystems indicated by the diagram.[7,8]

Transfers from forest and agricultural to freshwater and marine ecosystems are accomplished primarily by hydrological processes.[9] Transfers from one compartment to another within the terrestrial ecosystems are accomplished by a variety of transfer mechanisms most of which involve the movement of water and/or organic matter. For example, the transfer of radionuclides or stable elements from the leaf to the litter compartment of a forest may be due to the mechanical removal of fallout particles, the washing and leaching action of rain, leaf fall, deposition of herbivore excreta, etc. Transfers from the litter to the soil compartment involve decay processes, leaching by rain, percolation of water through the soil, etc. Transfers from the soil to the fruit or other edible parts of a plant involve root absorption, transpiration, translocation within the plant, and a variety of metabolic processes. A similar array of transfer mechanisms can be recognized for the pathways connecting other compartments; but, as will be illustrated later, it is often possible to obtain estimates of intercompartmental flow rates and other parameters used in ecological modeling without having an exact knowledge of the transfer mechanisms responsible for the flow.

General Approach to Mathematical Modeling

A mathematical model designed to simulate the entire process of radionuclide redistribution, even to the relatively low degree of resolution indicated by Figure 1, would be required to consider a large number of variables including (1) the more than 300 radionuclides produced by nuclear cratering explosions, (2) one or more patterns of predicted fallout deposition, (3) an indefinite number of ecosystems and all the materials transport pathways that characterize them, (4) the physical and/or biological transfer mechanisms that characterize each transport pathway, (5) an indefinite number of population subgroups depending on the ecological and cultural factors which determine variations in dietary habits, (6) a variety of physiological parameters which are different for different radionucldies and may vary with respect to age or other characteristics of population subgroups.

From a strictly scientific point of view, a detailed model considering all these parameters, especially if it had already been tested under realistic field conidtions, would provide an excellent basis for evaluating potential radionuclide intakes by people living in or near the area that would be contaminated by radioactive debris. However, for present purposes, it is neither necessary nor practical to consider all aspects of the radionuclide redistribution process. Many of the radionuclides produced by nuclear cratering explosions are produced in such small quantities or have such short radiological half-lives that their contributions to potential internal radiation doses are probably negligible. Many of the possible redistribution pathways are of little direct concern because they do not lead to man, and many of those that do lead to man are inconsequential because they represent foods that are consumed in very small quantities. Furthermore, the experimental data required for the development of a detailed model are neither readily available nor could they be collected during the time ordinarily available for a feasibility study. In many cases, where a detailed model could be used, it may still be desirable to use a simple model because the variations introduced by the detailed model are of little consequence, and the more sophisticated mathematical approach would needlessly complicate the overall model.

The approach we have taken is designed to simplify the problem as much as possible in order to concentrate our attention and efforts on the most important parameters affecting potential dose calculations. First, the production of 318 radionuclides was calculated for each of 22 detonations. Radionuclides having an inventory of less than one Curie 28 days after any detonation were assumed to make no significant contribution to the potential internal dose. This procedure eliminated all but 53 of the original 318 radionuclides from more detailed consideration. The 53 radionuclides remaining after the first screening were evaluated by means of a simple two-compartment model which, based on conservative assumptions concerning the general behavior of radionuclides in the biosphere, is used to calculate the maximum, probable contribution of each radionucldie to the internal radiation dose. The 22 radionuclides whose combined contributions added up to an insignificant dose (i.e., <1 rem infinite dose) were then eliminated from further consideration. The 31 radionuclides remaining after this step are now being evaluated on the basis of a generalized, multicompartment transport model which is more realistic than the two-compartment model but still contains a number of conservative assumptions and makes use of parameter values which tend to overestimate the potential radiation dose due to each radionuclide. This process of elimination will be repeated until only a few radionuclides need to be treated in the most complex transport model.

The advantages of this approach are that the number of radionuclides to be considered at each step is expected to decrease as the complexity of the model increases. Obviously, the most complex and presumably most realistic model in the series or hierarchy of models will be no better than the experimental data available for formulating the model and calculating the critical parameters. The present state of the art may not permit us to advance beyond the second or third stage in the hierarchy; but to the extent that the preliminary models are valid, they can be used to indicate the kinds of data required for developing more detailed transport models for the most important radionuclides in the most important ecological pathways leading to man. The next logical step in this procedure would be to test the different parts of the model under realistic field conditions, but we have not yet had an opportunity to take this step.

Modified Specific Activity Model

The simple, two-compartment model used for the second screening of radionucldies is based on a number of assumptions which Lowman[10] will probably discuss in greater detail. First, we assume that the radionuclides and stable elements released to the biosphere by a nuclear cratering explosion will become mixed with the stable elements already present in the biosphere. Radionuclides will then be redistributed by the same ecological processes and follow the same routes of transfer as their stable element counterparts. If the physical and biological processes involved in the transport of radionuclides and stable elements to man exhibit no significant discrimination between a radionuclide and its corresponding stable element, the specific activity (i.e., the ratio of the concentration of a radionuclide to the concentration of the corresponding stable element) of man's diet cannot exceed the specific activity of the radioactive debris.

In the two-compartment model, compartment 1 represents a hypothetical total diet, and compartment 2 represents a critical organ of "Standard Man." The specific activity of each radionuclide in compartment 1 is assumed to be the same as that of the radioactive debris produced by a nuclear cratering explosion. This is roughly equivalent to substituting radioactive debris for man's normal intake of each stable element and neglecting the dilution that would result due to mixing with the stable elements already present in the food.

Flow rates in and out of compartment 2 are based on the physiological data tabulated by ICRP[11] for "Standard Man." For each element, the flow rate from compartment 1 to compartment 2 is the product of the element ingestion rate and the fraction of the element ingested that reaches the critical organ. The flow rate out of compartment 2 depends on (a) the total amount of element, both radioactive and stable, present in compartment 2, (b) the biological elimination rate coefficient of the element, and (c) the radioactive decay rate coefficient of the radionuclide.

For all organs, except the gastrointestinal tract, the solution to the two-compartment model can be formulated as follows:

$$S_1 = S_1(0)\ \exp\ (-\lambda_R\ t) \tag{1}$$

$$Y_2 = \frac{F_{21}\ S_1(0)\ \exp\ (-\lambda_R\ t)}{\lambda_B}\ [1-\exp\ (-\lambda_B\ t)] \tag{2}$$

where, $S_1(0)$ is the initial specific activity of the radioactive debris,

λ_R is the radioactive decay coefficient,

Y_2 is the amount of radionuclide in compartment 2,

F_{21} is the element flow rate from compartment 1 to compartment 2,

and λ_B is the biological elimination rate coefficient.

The movement of material through the gastrointestinal tract cannot be adequately described by a biological elimination rate because the material does not remain in one place long enough for complete mixing to occur. An approximation for the average radionuclide content of a given portion of the tract is the product of the rate at which the radionuclide enters that portion and the time it takes material to traverse it. Allowing the radionuclide to decay during the time it takes ingested food to reach a particular portion of the gastrointestinal tract gives

$$Y_2 = F_{21}\, S_1(0)\, \tau_2 \, \exp(-\lambda_R t)\, U_{-1}(t-\tau_1) \qquad (3)$$

where, τ_1 is the time it takes ingested material to reach a given portion of the tract,

τ_2 is the time it takes ingested material to traverse that portion of the tract,

and U_{-1} is the unit step function defined by,

$$U_{-1}(x) = 0 \text{ for } x < 0$$

$$U_{-1}(x) = 1 \text{ for } x > 0.$$

The ICRP has also tabulated the data needed to calculate the dose rate to a critical organ of "Standard Man" per unit (Y_2) of radionuclide deposited in the critical organ. This value is the R term in Equation (4) and (5) below; it is a constant for a given radionuclide in a given critical organ. Equation (4) and (5) are obtained by multiplying Equation (2) and (3) by R and integrating the resulting expressions with respect to time. Equation (5) applies to the gastrointestinal tract while Equation (4) applies to all other critical organs.

$$D = R\,F_{21}\,S_1(0)\left[\frac{1}{\lambda_R\,(\lambda_B+\lambda_R)} - \frac{\exp(-\lambda_R\,t)}{\lambda_R\,\lambda_B} + \frac{\exp(-\,(\lambda_R+\lambda_B)\,t)}{\lambda_B\,(\lambda_B+\lambda_R)}\right] \qquad (4)$$

$$D = \frac{R\,F_{21}\,S_1(0)\,\tau_2}{\lambda_R}\left[\exp(-\lambda_R\,\tau_1) - \exp(-\lambda_R\,t)\right]U_{-1}\,(t-\tau_1) \qquad (5)$$

Equation (4) and (5) were used to calculate the maximum likely contributions of each of the 53 radionuclides whose inventory 28 days after at least one of the 22 detonations was one Curie or more to the critical organs listed by ICRP. The time interval considered for these calculations was from 28 days to 50 years after the last detonation.

Arranging the calculated dose contributions in descending order and calculating the cumulative sum indicated that 22 of the 53 radionuclides considered would contribute a total dose of slightly less than one rem. As a conservative estimate, a dose contribution of one rem can be assigned to all but the 31 radionuclides whose contributions to the potential dose are to be evaluated on the basis of a more detailed, more realistic model.

The procedure described above should result in highly conservative overestimates of potential internal radiation because it ignores the dilution effects of several important processes. In the first place, the estimates of initial specific activity, $S_i(0)$, are based on the assumption that radionuclides produced by a nuclear cratering explosion are mixed only with the amounts of stable elements contained in the fireball volume. Since experimental data[12] indicate that the radionuclides should be mixed with a much larger volume of stable elements, the radioactive debris actually released to the biosphere should have a much lower specific activity than that calculated for use in Equations (1) and (2). If it is true that radionuclides and stable elements follow the same transport pathways and exhibit the same ecological behavior, environmental and biological dilution, as well as the radioactive decay that will occur during the process of ecological transport from the biosphere to man, will further reduce and dilute the specific activities of radionuclides in man's diet. Since exclusion of these factors from the two-compartment model should result in overestimates of the contributions of nearly all radionuclides to the potential, internal radiation dose, we should not be far off in assuming that this model provides a valid method of reducing the list of radionuclides to be considered in the more detailed models of radionuclide redistribution in the biosphere and transport to man. [For simplicity's sake we'll call the radionuclides eliminated in this model "insignificant," and those remaining we'll call "significant."]

General Equations for Radionuclide Transport Models

Generally, we have assumed that the transport of "significant" radionuclides through food chains or food webs, such as illustrated in Figure 1, can be described by mathematical models consisting of first order, ordinary differential equations. This type of model is a logical extension of the model for radionuclide decay chains.[13] Similar models have been used by ICRP[11] to estimate maximum permissible concentrations of radionuclides in air and water and by several ecologists[14-17] for more general descriptions of ecosystems.

The general equation for the model is based on the assumptions that (1) the functional components or compartments of ecosystems are large enough that the average radionuclide or stable element content of a compartment can be described by continuous mathematics, (2) the radionuclide or stable element flowing into a compartment is completely mixed with the stable element and/or radionuclide already present in the compartment, and (3) the rate of a radionuclide or stable element transfer is given by the product of a transfer coefficient and the amount of radionuclide or stable element in the transmitting compartment. Thus the total flow of a radionuclide or stable element in and out of a given compartment in the food chain or food web can be formulated as shown in Equation (6) below.

$$\frac{d\,Y_i}{dt} = \sum_{\substack{n=1\\n\neq i}}^{N} \lambda_{in}\, Y_n - Y_i \sum_{\substack{n=1\\n\neq i}}^{N} \lambda_{ni}$$

or

$$\frac{d\,Y_i}{dt} + \lambda_{ii}\, Y_i = \sum_{\substack{n=1\\n\neq i}}^{N} \lambda_{in}\, Y_n \qquad i = 1, 2 \ldots N \qquad (6)$$

where, the i^{th} compartment is the compartment of reference and all other compartments are designated n,

Y_i is the amount of a radionuclide in the i^{th} compartment (μCi),

Y_n is the amount of a radionuclide in the n^{th} compartment (μCi),

λ_{in} and λ_{ni} are rate coefficients for transfers into and out of the i^{th} compartments (day^{-1}),

$$\lambda_{ii} = \sum_{\substack{n=1\\n\neq i}}^{N} \lambda_{ni}$$

and N is the total number of compartments

Usually, the λ_{in} and λ_{ni} values can be treated as constants or as cyclical functions of time, and this simplifies Equation (6) to a system of linear differential equations.

Each equation of the system of equations given by Equation (6) can be derived in different ways. The most direct method of derivation is possible if (a) the stable element content of each compartment of the ecosystem is known, (b) all the intercompartmental flow rates of the stable elements are known, and (c) it can be assumed that the behavior of a radionuclide is identical to that of the corresponding stable element. The material balance for a given radionuclide is then given by

$$\frac{d\,Y_i}{dt} = \sum_{\substack{n=1\\n\neq i}}^{N} \frac{F_{in}\,Y_n}{C_n} - Y_i\left(\frac{1}{C_i}\sum_{\substack{n=1\\n\neq i}}^{N} F_{ni} + \lambda_R\right) \tag{7}$$

$$i = 1, 2, \ldots N$$

where, the i^{th} compartment is the reference compartment and all other compartments are designated n,

Y_i and Y_n are the amounts of a radionuclide in compartments i and n (μCi),

F_{in} and F_{ni} are the total element, both stable and radioactive, flow rates into and out of compartment i (g. element/day),

C_i and C_n are the total element, both stable and radioactive contents of compartments i and n (g. element),

λ_R is the radioactive decay coefficient (day^{-1}),

$\sum_{\substack{n=1 \\ n\neq i}}^{N} \frac{F_{in} Y_n}{C_n}$ is the radionuclide flow rate into compartment i from all other compartments (μCi/day),

$Y_i \left(\frac{1}{C_i} \sum_{\substack{n=1 \\ n\neq i}}^{N} F_{ni} + \lambda_R \right)$ is the radionuclide loss rate from compartment I to all other compartments plus the loss rate due to radioactive decay (μCi/day),

and $\frac{d\,Y_i}{dt}$ is the rate of change of the radionuclide content of compartment i (μCi/day).

If the stable element contents of all compartments are constant and the intercompartmental flow rates are constants, the flow rates of stable elements into a compartment must equal the loss rate, i.e.,

$$\sum_{\substack{n=1 \\ n\neq i}}^{N} F_{in} = \sum_{\substack{n=1 \\ n\neq i}}^{N} F_{ni}$$

This, of course, implies an ecological steady state in which the biomass of the various ecosystem compartments, and the concentrations of different elements in each compartment, are more or less constant during the time interval considered. Such conditions appear to be approximated in climax forest ecosystems where the annual rates of community photosynthesis and community respiration are approximately equal and the biomasses of plant and animal populations are approximately the same from one year to another. For such a system, the principal data required to construct transport models based on Equation 7 are measurements or estimates of compartment capacities (C_i) and intercompartmental flow *rates* (F_{in}) *for the element or elements of interest.*

Compartment capacities can be estimated, on a unit area basis, as the product of compartment biomass (g biomass/m^2) and element concentration (g element/g biomass). Many of the intercompartmental flow rates can be obtained by measuring the rates of water and/or organic matter movement, and others can be inferred from these. Bloom[18] and McGinnis and Golley[19] provide excelent descriptions of how these procedures may be applied to a tropical forest eco-system.

If during the time interval considered, there is an increase in the biomass or stable element content of one or more of the compartments of an ecosystem, the system will not exhibit the kind of steady state equilibrium described above. There is, however, another kind of steady state condition which occurs when the total stable element content is a constant fraction of the weight or biomass of the compartment. In this case, the flow rate of the element into the compartment must equal the sum of the loss rates plus the rate of increase of element content due to growth of the compartment. This form of steady state has been used in the evaluation of radionuclide transport in marine ecosystems,[20] and it should be generally applicable to growing organisms.

Equation (8) is a generalization of the derivation given in reference (20).

$$\frac{d\,Y_i}{dt} = \left(\frac{d\,C_i}{dt} + \lambda_B\,C_i + \lambda_R\,\varepsilon\,Y_i \right) \sum_{\substack{n=1 \\ n \neq i}}^{N} \frac{f_{in}\,Y_n}{C_n}$$

$$- (\lambda_B + \lambda_R)\,Y_i \qquad i = 1, 2, \ldots N \qquad (8)$$

where, $\frac{d\,C_i}{dt}$ is the increase of total element content due to the growth of compartment i (g/day),

ε is a factor which converts radioactivity units to mass units (g/μCi),

f_{in} is the fraction of the element input to compartment i which comes from compartment n (dimensionless),

and $\sum_{\substack{n=1 \\ n \neq i}}^{N} f_{in} = 1.$

The relationship indicated by Equation (8) can be assumed for either plant or animal compartments of either stable or developing ecosystems. As will be illustrated in the discussion which follows, it can also be applied to cultivated crops.

A Simple Crop Model

The principal food plants cultivated in eastern Panama and northwestern Colombia are banana, plantain, rice, and corn. Banana and plantain are usually grown in semipermanent plantations and harvested throughout the year. Rice and corn are planted in fields which have been prepared by cutting and burning the secondary vegetation or mature forest and harvested once or twice per year. After a few years of cultivation, crop yields drop off and the fields are allowed to revert to secondary vegetation.

While a great deal is known about plant physiology and the uptake of minerals from soils, there is no general model for predicting the accumulation of fallout radionuclides in the edible parts of plants. Without experimental data from tracer experiments involving the principal radionuclides, different crop species, and various soil types of interest, the use of concentration factors may not be reliable. Analytical data show no consistent relationship between the concentrations of elements in paired samples of plant tissues and soil extracts.[21] However, the chemical composition of a given plant tissue is much less variable than that of the different soil types on which it is grown.

In developing a simple, conservative model to obtain rough estimates of radionuclide concentrations in the edible parts of crops grown in fallout contaminated areas, we have made the following assumptions:

(1) The element composition of the edible part is constant and can be defined by the mean element concentrations of representative samples.

(2) The concentration of an element in the plant compartment does not change during growth.

(3) The ratio of elements taken up from the soil and via translocation from foliage is the same as the ratio of elements in the compartment of reference, i.e., compartment 3 in Figure 2.

(4) All compartments are well mixed, in equilibrium with respect to total element content and not changing in biomass with respect to time.

These assumptions imply a situation in which harvesting is a continuous process, the rate of harvesting is equal to the growth rate, and the biomass of unharvested edibles is constant. This is a reasonable approximation to the harvesting of plantain and banana; and since lifetime doses are calculated on the basis of 50 or 70 years, it is not as bad as it might appear for annual crops. For short-term applications, models could be developed to represent the intermittent character of crop growth and harvest, but for the present application this does not appear to be warranted.

Equation (9) shows the assumed relationship between harvesting rate and the rate of total element input from foliage and soil.

$$H\ (X_3\ W_3) = k_{1,3}\ (X_1\ W_1) + k_{2,3}\ (X_2\ W_2) \tag{9}$$

where, H is the harvesting rate coefficient (years^{-1}),

X_j is the ratio of a given element to the total element content of the j^{th} compartment (dimensionless),

W_j is the average biomass or weight per unit area of the jth compartment (g/m^2),

$k_{1,3}$ is the translocation coefficient (years^{-1}),

and $k_{2,3}$ is the uptake coefficient (years^{-1}).

Values for these parameters can be estimated as follows:

(1) Since the harvesting rate and the growth rate are assumed to be equal, H is the harvesting rate or growth rate (g/m^2/y) divided by the average biomass (g/m^2).

(2) The average biomass, W_j, of the j^{th} compartment is, in this case, equivalent to the average standing crop of foliage or plant edibles; the value for soil is based on an arbitrary depth of soil, the depth of the interflow layer for example.

(3) Assuming $k_{1,3}$ values are very small, except for radionuclides, the $k_{2,3}$ values can be estimated using Equation 10 below.

$$k_{2,3} \cong H \frac{X_3\ W_3}{W_2\ X_2} \tag{10}$$

(4) The $k_{1,3}$ values can be determined by means of tracer experiments such as those described by Thomasson, Bolch, and Gamble[22] in which ^{134}Cs and other radionuclides were applied to banana and coconut leaves and samples of fruit were collected at various times after the tracer application. The transfer coefficient, $k_{1,3}$, can be determined from the observed exponential rate of radionuclide

accumulation in the fruit. The rate of foliar uptake of cesium is extremely rapid, and application of the transfer coefficient for cesium to other radionuclides should result in conservative overestimates of input rates.

Analytical solutions for the time variant concentration of a given radionuclide in each of the three compartments are given below for a pulse input to the system. The differential equation for the foliage compartment is

$$\frac{d N_1}{dt} = -(k_{1,2} + k_{1,3} + \lambda_R) N_1 \tag{11}$$

where, N_1 is the radionuclide content of the foliage compartment on a unit area basis (µCi/cm^2),

λ_R is the radioactive decay rate coefficient (day^{-1}),

and t is time (days).

For $t = 0$

$$N_1(0) = \bar{a}_L W_1 F_A \tag{12}$$

where, $\bar{a}_L$ is an interception coefficent (cm^2/g)[23]

W_1 is the average biomass of compartment 1 (g/cm^2)*

F_A is the fallout input for the reference radionuclide (µCi/cm^2).

The solution of Equation (11), the foliage compartment is

$$N_1 = N_1(0) \exp [-(k_{1,2} + K_{1,3} + \lambda_R) t] \tag{13}$$

or

$$S_1 = \frac{\bar{a}_L}{X_1} F_A \exp [-(k_{1,2} + k_{1,3} + \lambda_R) t] \tag{14}$$

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*The product, $\bar{a}_L W_1$, is the fraction of fallout intercepted by plant foliage.

where, $S_1\ (t) = \frac{N_1(t)}{W_1\ X_1}$ = specific activity.

The differential equation for compartment 2, the soil compartment, is

$$\frac{d\ N_2}{dt} = k_{1,2}\ N_1 - (k_H + k_{2,3} + \lambda_R)\ N_2 \tag{15}$$

where, N_2 is the radionuclide content of the soil compartment on a unit area basis (μCi/cm^2),

and k_H is a hydrological removal coefficient (day^{-1})^{24}.

For t = 0,

$$N_2(0) = (1 - \bar{a}_L\ W_1)\ F_A \tag{16}$$

i.e., the fallout not initially intercepted by foliage is deposited on the soil.

The solution of Equation (15), the soil compartment is

$$N_2 = N_2(0)\ e^{-\alpha_2\ t} + \frac{k_{1,2}\ N_1(0) \left[e^{-\alpha_2\ t} - e^{-\alpha_1\ t} \right]}{(k_{1,2} + k_{1,3}) - (k_H + k_{2,3})} \tag{17}$$

or $S_2 = \frac{N_2(t)}{X_2\ W_2}$ = specific activity of compartment 2 (18)

where $\alpha_1 = k_{1,2} + k_{1,3} + \lambda_R$,

and $\alpha_2 = k_H + k_{2,3} + \lambda_R$.

The differential equation for compartment 3, the plant edibles compartment, is

$$\frac{d\,N_3}{dt} = k_{1,3}\,N_1 + k_{2,3}\,N_2 - (H + \lambda_R)\,N_3 \tag{19}$$

where, N_3 is the radionuclide content of the plant edibles compartment on a unit area basis (μCi/cm^2).

For $t = 0$,

$N_3(0) = 0$

The solution of Equation 19, the plant edibles compartment, is

$$\begin{aligned} N_3 = {} & \frac{k_{1,3}\,N_1(0)\left(e^{-\alpha_3\,t} - e^{-\alpha_1\,t}\right)}{k_{1,2} + k_{1,3} + H} \\ & + \frac{k_{2,3}\,N_2(0)\left(e^{-\alpha_3\,t} - e^{-\alpha_2\,t}\right)}{k_H + k_{2,3} - H} \\ & + \left\{ \frac{k_{2,3}\,k_{1,2}\,N_1(0)}{(k_H + k_{2,3} - k_{1,2} - k_{1,3})(H - k_H - k_{2,3})(k_{1,2} + k_{1,3} - H)} \right. \\ & \times \left[(k_H + k_{2,3} - H)\,e^{-\alpha_1\,t} + (H - k_{1,2} - k_{1,3})\,e^{-\alpha_2\,t} \right. \\ & \left.\left. + (k_{1,2} + k_{1,3} - k_H - k_{2,3})\,e^{-\alpha_3\,t} \right] \right\} \end{aligned} \tag{21}$$

or $$S_3 = \frac{N_3(t)}{X_3\,W_3} \tag{22}$$ = specific activity of compartment 3

where, $\alpha_3 = H + \lambda_R$.

With reference to Figure 2, the first term of Equation (21) represents the fallout-to-foliage-to-plant edibles pathway of radionuclide transport; the second term represents the fallout-to-soil-to plant edibles pathway; and the third term represents the fallout-to-foliage-to-soil-to-plant edibles pathway. The movement of elements from soil to roots, stems, leaves, or other parts of the plant before deposition in the edible part of the plant, is not considered in the model. In other words, $k_{2,3}$, *is an overall transfer coefficient for* the general transport pathway from soil to plant edibles. It should also be noted that the pathway involving the transport to plant edibles of materials deposited externally on foliage rarely accounts for more than an insignificant fraction of the total element reaching the plant edibles compartment even though it may account for a major fraction of the radionuclide.

The derivation of analytical solutions given in Equation (11) through (22) serves to elucidate the general procedure. However when the models for different ecosystems are coupled to obtain a general model of radionuclide redistribution and transport to man, a number of complications arise which usually make it necessary to resort to numerical solutions. For example, constant hydrological removal coefficients, k_H, may not be appropriate; fallout input, F_A, varies geographically and, in the case of canal excavation, it cannot be adequately expressed as a single pulse.

A Simple Transport Model for Terrestrial and Aquatic Ecosystems

Figure 3 illustrates an eight-compartment transport model in which the pathways illustrated in Figure 2 are coupled to other pathways leading from terrestrial and aquatic ecosystems to man. While the eight-compartment model is more complex and more realistic than the models described earlier, it represents a much lower degree of resolution than illustrated by Figure 1 and still incorporates a number of highly conservative assumptions.

As shown in Figure 3, man's total diet is assumed to be composed of specific quantities of fish, surface water, plant edibles, and terrestrial animals. The quantities used were selected to represent the population groups having the highest fish consumption, the highest water consumption, the highest consumption of plant materials, and the highest consumption of terrestrial animals. Describing the total diet according to these criteria results in a hypothetical food and water intake almost twice as high as the intakes actually observed by anthropologists who made quantitative dietary studies in the field.[7,8]

Values for the element contents of the compartments and for the intercompartmental transfer coefficients were selected, on the basis of data collected by field survey teams and data in the literature, to represent average or typical values of the sort indicated. In cases where "average" or "typical" values were in doubt, other values were selected arbitrarily to maximize the final dose estimates. To further increase the conservatism of the results, fallout input was calculated on the assumption that all detonations occur at the same time. The most heavily contaminated watershed was selected as the worst place that humans could possibly be, and dry season rainfall rates were used to minimize the rate of flushing from the land to the sea.

The radionuclides evaluated by the eight-compartment model were the 31 radionuclides remaining after application of the two-compartment specific activity model, namely - ^{3}H, ^{14}C, ^{32}P, ^{89}Sr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{124}Sb, ^{125}Sb, ^{127m}Te, ^{129m}Te, ^{131}I, ^{132}Te, ^{141}Ce, ^{143}Pr, ^{144}Ce, ^{151}Sm, ^{155}Eu, ^{181}W, ^{185}W, ^{188}W, ^{195}Au, ^{196}Au, ^{203}Hg, ^{210}Pb, ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu. Typical dose estimates obtained by this procedure are given in Table I. The calculation for zero time to infinity indicates that the cumulative dose contributed by 5 of the 31 radionuclides (^{124}Sb, ^{125}Sb, ^{127m}Te, ^{151}Sm, and ^{155}Eu) would total less than one rem. Allowing all radionuclides to decay for 100 days and calculating the dose from 100 days to infinity indicated that the contribution from 11 of the 31 radionuclides would be less than one rem. (These 11 include the 5 listed above plus ^{32}P, ^{95}Nb, ^{132}Te, ^{143}Pr, ^{195}Au, and ^{196}Au). The data from which those in Table I have been selected provide a clear indication that ^{3}H, ^{89}Sr, ^{90}Sr, ^{106}Ru, and some 16 other radionuclides not shown in the table will require further evaluation.

TABLE I. TYPICAL DOSE CALCULATIONS BASED ON THE EIGHT-COMPARTMENT MODEL

	Dose (rem) calculated for	
Radionuclide	Time zero to ∞	100 days to ∞
^{90}Sr	685	680
^{3}H	673	663
^{132}Te	586	~0
^{89}Sr	316	80
^{106}Ru	106	88
^{127m}Te	4.3×10^{-1}	2.2×10^{-1}
^{151}Sm	5.3×10^{-3}	5.3×10^{-3}

At this point it should be strongly emphasized that the only dose estimates in Table I that should be taken seriously are those whose sum is less than one. The area considered in obtaining these figures is one that would be completely evacuated during the nuclear evacuation phase of the canal construction program and would not be reoccupied until some time after the last detonation. It was chosen to represent the worst case we could imagine. We feel that this approach provides a valid basis for identifying those radionuclides which contribute very little to the potential radiation dose, and that the actual contribution of all these radionuclides can be assigned a conservative but relatively insignificant value. The 20 radionuclides remaining in the "significant" category at this stage of the study, are being re-evaluated by means of more detailed models which are as realistic as we can make them on the basis of present information. In many cases, this re-evaluation will have a profound effect on the dose estimates. For example, a recent recalculation of the tritium dose was based on the best information available on hydrologic redistribution. The new calculation was made for the same "hottest" watershed and used the same conservative dietary input, but the new dose estimate for tritium is more than two orders of magnitude less than the value given in Table I.

In the first application of the eight-compartment model, a Laplace transform technique[25] was used to calculate the infinite time doses directly. Using a semianalytical method[25,26] of solving the differential equations, a computer program was designed to calculate the concentrations of radionuclides in each compartment as a function of time. The results for ^{90}Sr, normalized for a unit fallout input of ^{90}Sr, are shown in Figures 4-9.

Figure 4 shows the time dependent concentrations in the foliage and herbivore (soft tissues) compartments. The curve for plant leaves reflects the initial contamination by fallout and the rapid exponential rate of loss due to weathering. The rate coefficient used in this example corresponds to a weathering half-time of 14 days, a value reported frequently in the literature.[27] A growing body of experimental evidence[28] indicates that the rate of loss from leaves would be better described by a two- or three-exponent model, but lacking the experimental data from which "typical" values of the two or three exponents can be calculated, the single-exponent model is retained as a useful approximation. The curve for herbivores peaks about 15 days after time zero, and then decreases at a rate eventually approximating the rate of loss from leaves. This reflects the relatively rapid turnover time for ^{90}Sr in soft tissues compared to bone.

Figure 5 shows the relative concentration in soil water from time zero to about 2,400 days. The turnover rate for soil water[19] is considerably fastern than might be inferred from this graph; the slow depletion rate for ^{90}Sr is due to the soil's high absorptive capacity for strontium.[29] To compensate for having used a low depletion rate to maximize ^{90}Sr concentrations in the terrestrial compartments, and to maximize the estimates of ^{90}Sr transport to man via water and fish, ^{90}Sr concentrations in the surface water compartment were assumed to be the same as those in the soil water compartment. If the other parameters are correct, this has the same effect as ignoring the ground-water contribution to stream flow.

The results for the fish compartment, Figure 6, were primarily determined by an assumed concentration factor of 10^3 and by the assumed time variant concentration of ^{90}Sr in the water. The rapid buildup in the fish compartment is due to the assumption of a fairly rapid turnover time.

Figure 7 shows the calculated ^{90}Sr concentrations in the plant edibles compartment for only the first 80 days after fallout. This part of the curve illustrates the relative importance of foliar uptake during the first few weeks after fallout. The late-time behavior of this curve, not shown in the figure, would be governed by uptake from the soil-soil water compartment.

The curve for the critical organ (bone) of man is shown in Figure 8. Under the conditions prescribed by the eight-compartment model, the peak value is reached about 2,500 days after fallout deposition, a time at which the concentrations in most other compartments have declined to levels which are insignificant in comparison to the maximum values. The slow decline in this compartment does not reflect the fairly rapid decline in most other compartments. Instead, it is governed by the long half-life of ^{90}Sr and the slow rate of biological elimination from the skeleton. The integral of this curve is plotted in Figure 9 to show the cumulative radiation dose to bone, the critical organ of man for ^{90}Sr, as a function of time. Although still increasing, its value after about 50 years is approximately 90 percent of the infinite dose. This illustrates the utility of the simple $0 \rightarrow \infty$ integrals for approximation.

In this particular example, about half of the 50-year dose was due to the fish pathway, about a quarter was due to plants, a little less than a quarter came from terrestrial animals, and a very small fraction came from water. The high contribution from fish is partly due to assumption that fish are eaten bones and all. In some cases this assumption is well borne out by direct observations.

DISCUSSION

Before closing, we should again emphasize that the eight-compartment model and the results presented above are provisional. They are presented here only to illustrate the methods being used to develop ecological models of radionuclide transport. The parameters used in this preliminary effort were deliberately chosen to represent the worst possible case. There were many reasons for doing this, but the major ones were (1) to compensate for uncertainties in the model parameters and other input data, and (2) to increase the level of confidence in our identification of radionuclides whose total contribution to the potential internal radiation dose is likely to be insignificant. Since these results were first reported about seven months ago,[25] considerable progress has been made toward increasing the adequacy of the model. Additional compartments have been added to account for radionuclide transport to man from the marine ecosystem. Fallout inputs to the "hottest" watershed have been recalculated on the basis of the proposed detonation schedule (22 detonations over a period of approximately three years). Instead of using "average" or "typical" values for all the elements involved, we have tried to calculate realistic parameter values for each element, or at least for each of the elements for which we have analytical and/or experimental data of the proper sort. Once the model has been refined to the extent made possible by the data available, the lifetime internal dose estimates for the hottest watershed will be recalculated to determine how soon after the last detonation it would be safe for people to reoccupy the fallout area. One method of doing this would be to let the fallout model run continuously from the beginning of the detonation schedule and then to introduce man into the model at various times after the last detonation. A graphical method of solving the reoccupancy problem may be even more convenient. This would involve the computation of cumulative dose curves, such as shown in Figure 9, for each radionuclide. The effect of delayed reoccupancy could then be evaluated directly from these graphs.

Present plans for the canal excavation project call for the establishment of an exclusion area, i.e., an area to which local fallout could be confined and from which people would be excluded until some time after completion of the nuclear excavation. The boundaries of the exclusion area are more than ample to enclose the 0.5 R lifetime external gamma dose contour of the composite fallout pattern. When it has been completed, the ecological model will be used to estimate the maximum probable internal radiation doses to people living outside the exclusion area. Fallout input will be calculated as equivalent to deposition along the 0.5 R external dose contour, and food intakes will be adjusted to reflect variations in the diets of different age groups and different cultural groups. By adjusting the fallout input terms, this version of the model could also be used to calculate the radiation doses to which people might be exposed if higher levels of fallout were accidentally deposited in populated regions outside the exclusion area.

If the peaceful uses of nuclear explosives for excavation projects are shown to be feasible and research activities continue in the area of ecology, we should have many opportunities to test and improve these models to a point of reliability at least equal to the methods now available for predicting fallout deposition patterns and external radiation doses. Perhaps some golden day in the not too distant future we will have at our disposal a vast library of proven parameter values to fit almost any combination of radionuclides and ecological transport mechanisms. Meanwhile, we hope the preceding discussion has indicated some of the procedures that can be used, providing the results are judiciously interpreted, until that golden day should arrive.

REFERENCES

1. Martin, W. E., 1969. Radioecology and the Feasibility of Nuclear Canal Excavation, pp. 9-22 in: D. J. Nelson and F. C. Evans (eds.) Symposium on Radio-Ecology. U. S. A. E. C., Conf-670503.

2. Martin, W. E., 1969. Bioenvironmental Studies of the Radiological-Safety Feasibility of Nuclear Excavation. BioScience 19(2):135-137.

3. Klement, A. W., 1969. Radiological Safety Research for Nuclear Excavation Projects - Interoceanic Canal Studies. (This Symposium).

4. Fleming, E. H., 1969. Radioactivity Source Terms for Cratering Applications. (This Symposium).

5. Mueller, H. F., 1969. Meteorological Requirements and Operational Fallout Prediction Techniques for Plowshare Nuclear Experiments. (This Symposium).

6. Kaye, S. V. and P. S. Rohwer. 1969. Methods of Estimating Exposure to Populations from Plowshare Applications. (This Symposium).

7. Araúz, Reina Torres de. 1969. Demographic and Dietary Data for Human Groups Inhabiting the Eastern Region of the Republic of Panama. *BioScience 19(4):(in press).*

8. McBryde, F. W. and Alfredo Costales. 1969. Human Ecology of Northwestern Colombia. BioScience 19(5):(in press).

9. Werner, L. B. 1969. Radioactivity in the Hydrologic Environment. (This Symposium).

10. Lowman, F. G. 1969. The Effects of the Marine Biosphere and Hydrosphere upon the Specific-Activity of Contaminant Radionuclides. (This Symposium).

11. International Commission on Radiological Protection. 1959. Report of Committee II on Permissible Dose for Internal Radiation. Pergamon Press, N. Y. 233 pp.

12. Fleming, E. H. *Personal communication.*

13. Overman, R. T. and H. M. Clark. 1960. Radioisotope Techniques. McGraw Hill, N. Y.

14. Patten, B. C. 1966. Systems Ecology: A Course Sequence in Mathematical Ecology. BioScience 19(9):593-599.

15. Olson, J. S. 1964. Gross and Net Production of Terrestrial Vegetation. J. Ecol. 52:99.

16. Martin, W. E. 1965. Early Food Chain Kinetics of Radionuclides Following Close-In Fallout from a Single Nuclear Detonation. pp. 758-790, In: A. W. Klement, Jr. (ed.) Radioactive Fallout from Nuclear Weapons Tests. U. S. A. E. C., Symposium Series 5, 933 pp.

17. Kaye, S. V. and S. J. Ball. 1969. Systems Analysis of a coupled Compartment Model for Radionuclide Transfer in a Tropical Environment, pp. 731-739, in: D. J. Nelson and F. C. Evans (eds.). Symposium on Radioecology, U. S. A. E. C., Conf-670503.

18. Bloom, S. G. 1967. Mathematical Formulation of the Hydrogen Budget Model. in: H. T. Odum, Hydrogen Budget and Compartments in the Rain Forest at El Verde, Puerto Rico. U. S. A. E. C. Rept., BMI-171-002.

19. McGinnis, J. T. and F. B. Golley. 1969. Elemental and Hydrological Budget of a Panamanian Rainforest. BioScience 19(8):(in press).

20. National Academy of Sciences, National Research Council. 1962. Disposal of Low-Level Radioactive Waste into Pacific Coastal Waters. Publ. No. 985.

21. Gamble, J. F. and S. C. Snedaker. 1969. Final Report - Agricultural Ecology. U. S. A. E. C. Report BMI-171-020 (in press).

22. Thomasson, W. N., W. E. Bolch, and J. F. Gamble. 1969. Uptake and Translocation of ^{134}Cs, ^{59}Fe, ^{85}Sr, and ^{185}W by Banana Plants and a Coconut Plant following Foliar Application. BioScience 19(7):(in press).

23. Miller, C. F. 1963. Fallout Nuclide Solubility, Foliage Contamination, and Plant Part Uptake Contours. SRI Proj. No. IMU-4021.

24. Charnell, R. L., T. M. Zorich, and D. E. Holly. 1969. Hydrological Redistribution of Radionuclides around a Nuclear-Excavated Sea-Level Canal. BioScience 19(9):(in press).

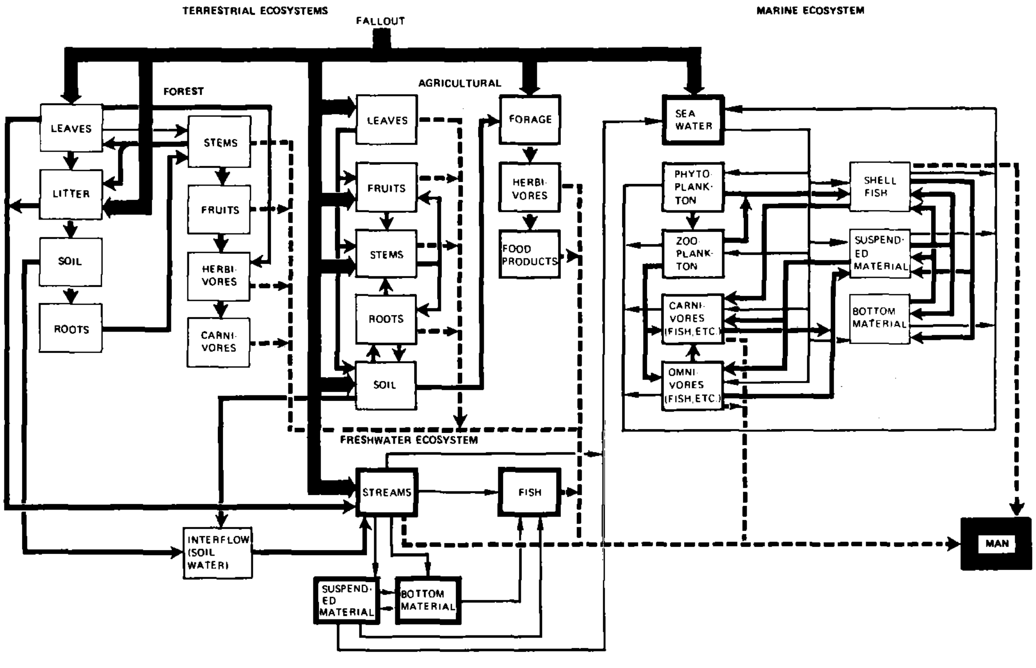
25. Raines, G. E., S. G. Bloom, and A. A. Levin. 1969. Ecological Models Applied to Radionuclide Transfer in Tropical Ecosystems. BioScience 19(11):(in press).

26. Ball, S. J. and R. K. Adams. 1967. MATEXP, a General Purpose Digital Computer Program for Solving Ordinary Differential Equations by the Matrix Exponential Method. U. S. A. E. C. Rept., ORNL-TM-1933.

27. Martin, W. E. 1964. Losses of ^{90}Sr, ^{89}Sr, and ^{131}I from Fallout Contaminated Plants. Radiation Botany 4:275-284.

28. Witherspoon, J. B. and F. G. Taylor, Jr. 1969. Retention of Fallout Simulant Containing ^{134}Cr by Pine and Oak Trees. Health Physics (in press).

29. Goldsmith, W. A., W. E. Bolch and J. F. Gamble. 1969. The Retention of Selected Radionuclides from Dilute Solution by Panama Clays. BioScience 19(7):(in press).



GENERALIZED RADIONUCLIDE TRANSPORT DIAGRAM

Fig. 1. Generalized Radionuclide Transport Diagram

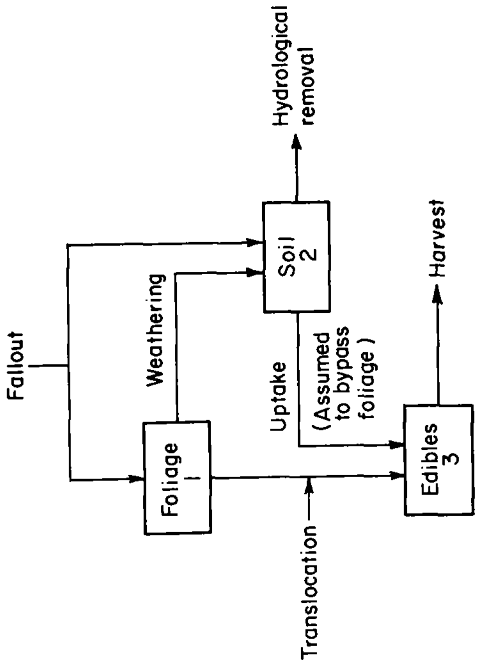


Fig. 2 Simple Crop Model Diagram

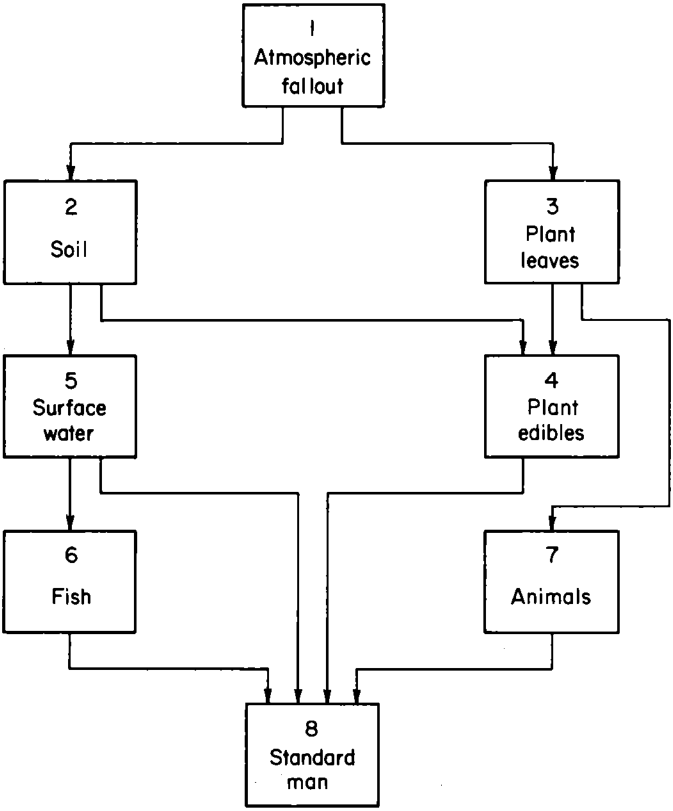


Fig. 3. Eight-Compartment Model Diagram

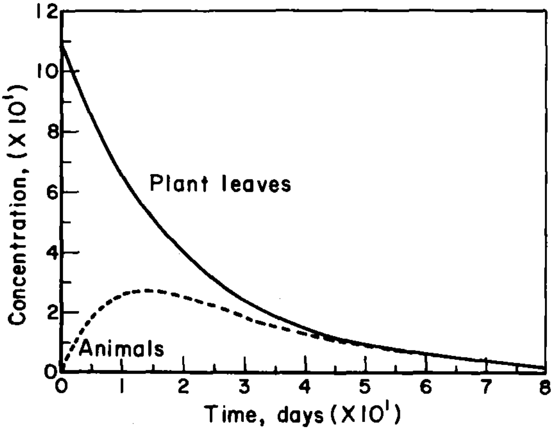


Fig. 4. Hypothetical Concentration of ^{90}Sr in Plant Leaves and Animal Flesh

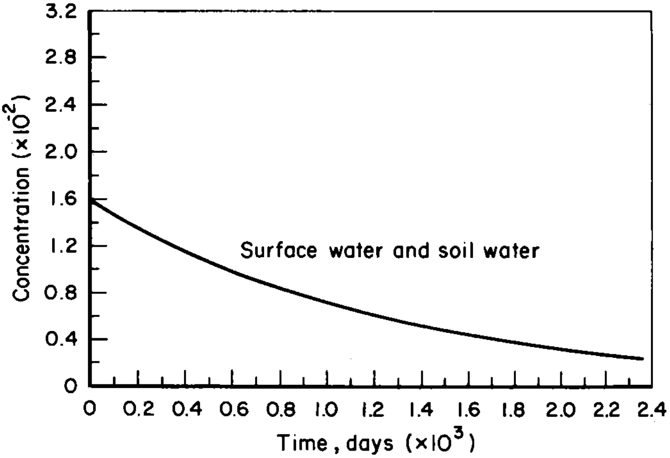


Fig. 5. Hypothetical Concentration of ^{90}Sr in Surface Water Soil Water

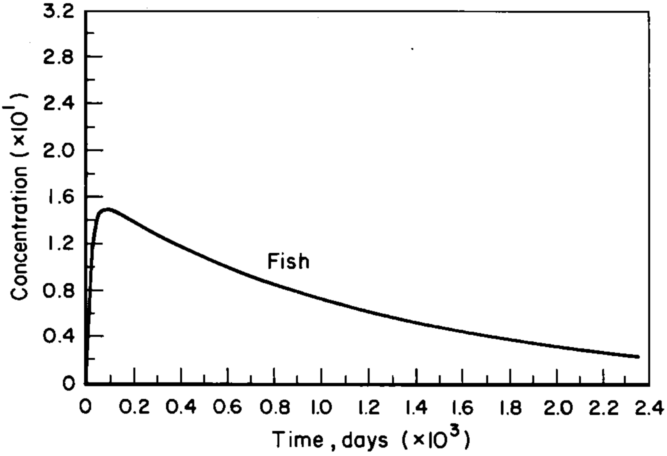


Fig. 6. Hypothetical Concentration of ^{90}Sr in Fish

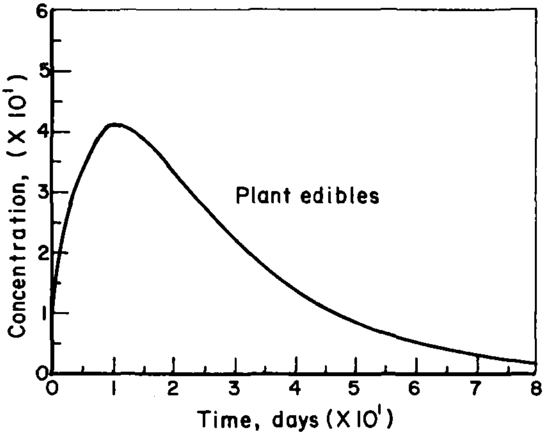


Fig. 7. Hypothetical Concentration of ^{90}Sr in Plant Edibles

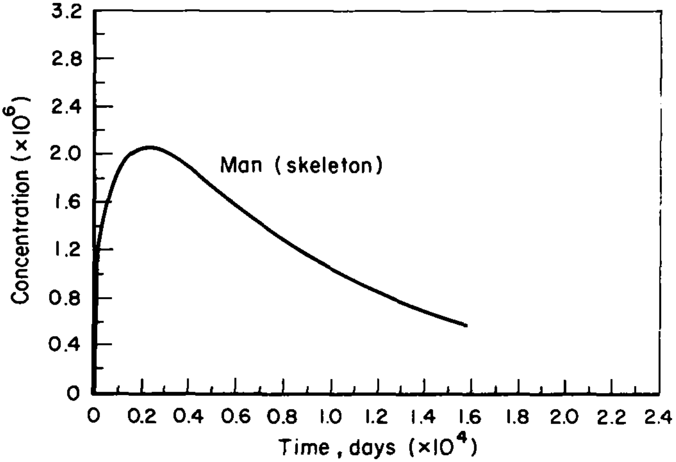


Fig. 8. Hypothetical Concentration of ^{90}Sr in Man (Skeleton)

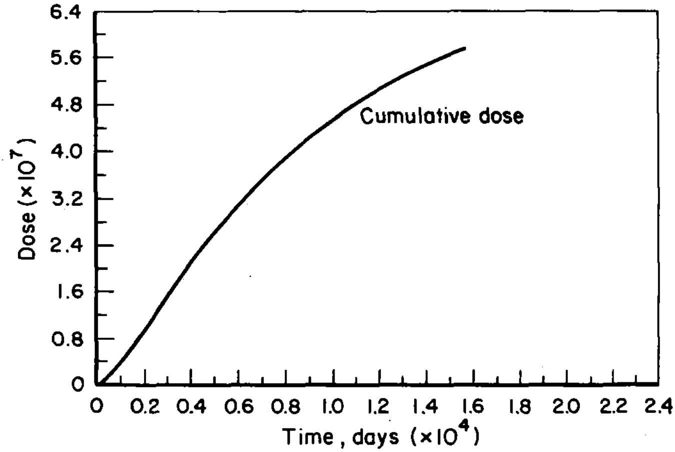


Fig. 9. Hypothetical Radiation Dose, Cumulative, to Man

QUESTIONS FOR WILLIAM E. MARTIN

1. From Dr. Pendleton:

Cesium-137 has been shown to increase by a factor of about three between trophic levels. Do your evaluations include this factor for dose estimation for men?

ANSWER:

To answer that truthfully, I have to look at the 200 values that go into the equations. This does happen in many of the food chains as a result of the differences of intake and elimination coefficients, so that there are cases where these concentrate in the food chain and other cases where they do not.

Moderator: To briefly summarize for the record what Dr. Pendleton just said, he feels that it is important to consider such factors and for example if you do have an increase of a factor of three for each trophic level and you are talking about as many as three trophic levels, then your final estimate could be low by a factor of ten if these factors are not taken into consideration.

ANSWER:

I agree with Dr. Pendleton 100%. But making precise measurements in some cases we feel that even if we checked our equations, we do get these buildups, but then when we look at the specific activity concept, in other words the idea that the transfers of the stable element and the radionuclide will be the same ratio, we come to the conclusion that we have created radioactivity somewhere in the process and we wind up with no radioactivity in the biosphere when it's produced by an explosion. I have not been able to explain this result.

2. From Dr. Pendleton:

Radionuclides on the soil surface may be transferred to foliage by rain splash or dust. Have secondary transfers of this kind been studied?

ANSWER:

No. In fact in the model we're using, runoff is somewhat unrealistic in that the nature of runoff is not surface runoff, but overflow in a very shallow hole in the soil near the surface. So we are assuming that that layer is a mixed type which, of course, it is not. In any case, we have made no effort to include the splash back from soil to foliage.

3. From M. Chessin:

To what extent are national or international radiological safety services or commissions involved in radiation hazards evaluations of the nuclear sea level canal projects?

ANSWER:

I don't know the answer to that. We are given to make dose estimates as realistically or as critically as we can, so that they can be compared to any criteria or standard that is adopted. We have ourselves nothing to do with the establishment of these standards.

4. From M. E. Wrenn:

Milk in Jamaica and some areas in Florida currently contain concentrations 10 to 100 times more cesium-137 than we would predict using transfer coefficients characteristic of more temperate latitudes. Other areas of the world have been identified where cesium-137 in milk is in the similar excess of expected values. These include New Zealand, Australia and more recently Chile. Do your transfer coefficients for cesium-137 reflect these anomalously high values or the more usual estimates?

ANSWER:

I heard about these results and I find them intriguing. I don't know why this should occur. I don't know their transfer coefficients from cesium-137. This is one of the radionuclides that drops out of consideration on other bases.

THE EFFECTS OF THE MARINE BIOSPHERE AND HYDROSPHERE UPON THE SPECIFIC ACTIVITY OF CONTAMINANT RADIONUCLIDES

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Mayaguez, Puerto Rico

ABSTRACT

Fusion and fission products as well as neutron-induced radionuclides will be produced by the use of nuclear explosives for excavation. Stable elements from the geological matrix which are vaporized at the time of detonation will be vented in the same form as the radionuclides and will dilute the radionuclides to different specific activities depending upon the yield and design of the explosive, the neutron flux, neutron cross-sections for the stable elements and the homogeneity of the rock. Radionuclides in the cloud and fallout may be further diluted by pulverized rock on which they plate although the chemical forms may or may not be the same. This fallout material may be deposited into the sea and will react with sea water and its contained salts to precipitate or co-precipitate some radionuclides and release others as colloids or solutes where they will be subject to further dilution by the stable elements in sea water. The radionuclides will be subjected to varying amounts of physical and chemical dilution according to the physical environmental parameters. In some estuarine and upwelling areas of high biological productivity, the radionuclides and corresponding stable elements may become incorporated into cycles involving the biosphere, hydrosphere and bottom sediments in which the added material will remain in the area for longer periods of time than that expected from physical mixing and dilution.

* *

Health physicists have traditionally and effectively defined hazards resulting from the ingestion of radionuclides in water on the basis of maximum permissible concentrations (MPC) of the contaminants in drinking water. Radioecologists have occasionally tried to apply MPC values for water directly to problems provided by contaminated food organisms, usually with unsatisfactory results (Lowman, et al, 1957). Major errors result from the application of MPC values to food because the MPC values for water were calculated for conditions in which no allowance was made for isotope dilution in the environment or in food webs leading to man.

In 1960 another method of assessing hazards in the marine environment was proposed by the National Academy of Sciences-National Research Council, Committee on Oceanography and Fisheries in their 1960 summary report. The method was based on the use of the maximum permissible specific activity (MPSA)* for radionuclides in critical organs and tissues of man. Values of MPSA may be derived from the data provided by the International Committee on Radiation Protection (ICRP). The method is based on the premise that marine organisms do not discriminate between isotopes of most elements** and that the specific activities in food items cannot exceed those in the environments. This relationship exists because the radionuclides derived directly or indirectly from the environment undergo additional isotope dilution from the corresponding stable elements in the food organisms.

The MPSA approach relates a given radionuclide to the corresponding stable element and may be used for hazards prediction by determining: (1) the distribution of the stable elements in the biogeochemical system, (2) physical and isotope dilution rates for the radionuclides in the environment and (3) biological half-lives in food organisms of man. The approach provides a method for the step-by-step evaluation of isotope dilution of an introduced radionuclide as it passes through the hydrosphere, geosphere and biosphere to man. The method does not require the determination of environmental and biological compartments for each radionuclide or detailed transfer routes and rates in food webs. Values for elemental compartments in both the environment and the organisms vary greatly under natural conditions and minor errors in the measurement of compartment values may introduce serious errors in prediction.*** In most marine areas the total biomass usually accounts for 10^{-6} or less of the total mass of the biogeochemical system actively associated with biologically-important elements. Because of this, the organisms normally exert an insignificant influence upon the distribution patterns of added contaminants. They may, however, provide transport of radionuclides to man through his food.

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* MPSA used in this report refers to the amount of the radionuclide in µCi per gram of the corresponding stable element allowed in the critical organ of man. The specific activity which is allowed is dependent on the annual radiation dose levels recommended by the ICRP for the general population in which it is possible to identify the population group expected to receive the highest dose. Equal to 1/10 the continuous exposure allowed to occupational workers.

**In the case of the very light elements, organisms usually discriminate against the heavier isotopes.

***See next page.

A simplified approach to predicting hazards in the marine environment may be based on the documented premise that environmental mechanisms provide the predominant controls for the distribution and movement of individual radionuclides and that the organisms reflect the resulting patterns. For most plants and animals the patterns are modified by biological turnover times which determine the rates at which the organisms approach the specific activity of any given radionuclide in the medium in which they live.

The MPSA approach is subject to errors in those cases where diluent stable elements are not in the same chemical or physical form as the introduced radionuclides. These errors are also of consequence in the use of the MPC method. In the sea the transition elements and other elements which tend to form complexes with organic material are mainly involved in this type of error. Thus, the uptake of iron by diatoms is enhanced for newly-added iron in comparison with "aged" iron (Johnston, 1964). Stable zinc is mostly chelated in sea water while newly-added zinc is largely ionic for appreciable lengths of time (Bernhard, M. - personal communication). Fortunately, the errors introduced by differences in physical and chemical form may be assessed by polarography, micropore filtration, dialysis, analysis of exchange reactions and by extraction methods.

The specific activity method may be applied to feasibility studies for a sea-level isthmian canal in Western Panama or northwestern Colombia as follows:

1. Calculate the specific activity in the ejecta for all radionuclides produced in amounts greater than 1.0 millicurie per megaton of explosive yield. Assume the radionuclides to be diluted by the vaporized and melted material. Delete from consideration the elements whose radionuclides occur at an initial ratio "specific

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***Transfer coefficients for most stable elements change with the total amounts of element available in the environment. This is especially true for many of the trace elements. Thus, the uptake of iodine in the thyroids of animals is not directly related to the amounts of available iodine; "iodine block" may occur with the presence of excessive amounts of the element in the environment. Under these conditions the accumulation of iodine-131 tracer would be reduced in the thyroids. Similar relationships of transfer to total amount of available element exist for iron, cobalt, strontium (plus calcium) and several other elements. In areas of fallout the specific activity of each radionuclide, at the time of deposition, may be expected to be fairly constant but the amounts of deposited radionuclides and corresponding stable element will both vary greatly according to the fallout pattern. The transfer coefficient for a given radionuclide from the environment to primary producers (or to higher trophic levels) may thus, also vary significantly according to fallout pattern.

activity"/"maximum permissible specific activity" (SA/MPSA) of less than 1.0.

2. For the radionuclides ejected with SA/MPSA ratios greater than one, determine the distribution patterns of the corresponding stable elements in the waters, sediments and organisms of the marine areas near the proposed routes.

3. Measure and calculate physical dilution rates, suspended sediment contents, sediment adsorption rates and sedimentation rates in the marine areas of interest. Use these data to calculate physical and isotope dilution and sedimentation of added radionuclides.

4. Assemble data on turnover rates in food organisms of marine origin. Calculate biological delay in transfer of radionuclides through food to man.

5. If estimates of daily intake of radionuclides are desired for use in MPC considerations of foods from other sources, calculate the concentration of each radionuclide per unit weight of food by multiplying the specific activity of the radionuclide (μCi/g) by the weight of the corresponding stable element in the unit weight of food. Use data for human feeding habits to determine total daily intake.

These calculations have been done and are presented elsewhere. (Ting, R. Y. 1969). The present discussion is concerned with the environmental and biological factors which influence and alter the specific activities of the radionuclides ejected from the excavations.

The specific activities of the material ejected from the nuclear excavations are directly dependent upon the design and efficiency of the explosives. Any reduction in the production of radionuclides will result in proportionate decreases in the specific activities of these nuclides in the ejecta. The estimates of radionuclide production used in this paper are based on the "Planning Information Statement" of the USAEC (Warner, 1957) and the report of Ng (1965) on neutron activation of the terrestrial environment from underground explosions. Warner provided data for the amounts of three radionuclides of geological origin, sodium-24, phosphorus-32 and calcium-45, in the cloud and fallout. The amounts of phosphorus-32 and calcium-45 were 3×10^{-5} the production values reported by Ng for the same nuclides. The latter values were for total activation and were not corrected for neutron shielding, scavenging during venting or special emplacement techniques. The ratio, 3×10^{-5}, was used in the present work to estimate, from Ng, the amounts of the other radionuclides in the cloud and fallout which would be produced from activation of the geological matrix. Estimates for production of vaporized and melted rock are based on the reports of Boardman, Rabb and McArthur (1964); Johnson, Higgins and Violet (1959); and Nordyke and Williamson (1965).

The ratio Specific Activity/Maximum Permissible Specific Activity for individual radionuclides in the fallout and cloud may be used to determine which of the nuclides provide potential hazards to man. SA/MPSA values greater than 1 for radionuclides produced by a 1 Mt shot in granite are shown in Table 1, Column 3. The changes in specific activity of the ejecta with size of detonation are shown in Figure 1.

From a total of 72 radionuclides produced in amounts greater than 1 millicurie per megaton of explosive yield, 23 would be ejected in the fallout and cloud at specific activities greater than those allowed in man. These include tritium, sodium-24, phosphorus-32, calcium-45 calcium-47, scandium-47, scandium-48, manganese-54, manganese-56, arsenic-76, bromine-82, rubidium-86, strontium-89, molybdenum-99, cadmium-115, iodine-131, technetium-132, barium-140, wolfram-185, wolfram-187, gold-198, and lead-203. Three mechanisms tend to reduce the specific activities of the radionuclides in marine waters; physical radioactive decay, isotope dilution by the corresponding stable element in sea-water and co-precipitation into or adsorption onto the bottom sediments. Although manganese-56 would initially occur in the cloud and fallout at a specific activity 345,000 times that allowed in the GI tract of man, its short physical half-life of 2.57 hours could cause it to decay to the specific activity allowed in man in 2 days. Scandium-47 would also decay to MPSA in 2 days, gold-198 in 3.3 days, cadmium-115 in 4 days, bromine-82 in 4.9 days, arsenic-76 in 7 days, wolfram-187 in 8.4 days, rubidium-86 in 9 days and scandium-48 in 9.7 days. Radionuclides which would decay to MPSA in 10 to 30 days include sodium-24 and tellurium-132 (13 days), molybdenum-99 (16 days), calcium-47 (23 days) and lead-203 (28 days). Eight of the 72 radionuclides would require 11 weeks or longer to decay to the specific activities allowed in man, if they were not diluted with the corresponding stable elements in the environment. These include barium-140 (77 days), iodine-131 (126 days), strontium-89 (165 days), wolfram-185 (167 days), phosphorus-32 (196 days), calcium-45 (620 days), manganese-54 (754 days) and tritium (97,000 days).

Considerable physical and isotope dilution occurs in the sea. Tritium, in fallout from underground nuclear detonations, would occur mainly as tritiated water and would be diluted by normal water in marine areas of turbulence. The water content of most marine organisms is less than 0.9 grams/gram of living material, however, hydrogen from water also may be incorporated into carbohydrates, lipids and proteins by marine plants, including phytoplankton. Even here the hydrogen content of the organisms seldom exceeds that in an equal amount of sea water so that the organisms normally concentrate hydrogen at factors of one or less. Calcium-45, strontium-90 and wolfram-185 from nuclear excavations would also not be concentrated significantly by marine organisms over the amounts in the water. In contrast, the other radionuclides added to the sea at specific activities greater than those allowed in man, and for which 11 weeks or more would be required to decay to MPSA, are accumulated by marine organisms to levels many times those in sea water. Thus, phytoplankton are able to concentrate phosphorus, 34,000; iodine, 5,000; barium, 17,000; lead, 40,000; and manganese, 4,000 times the levels in a corresponding weight of sea water. If the corresponding radionuclides of these elements deposited in fallout were not diluted in the environment and in food organisms eaten by man, potentially hazardous amounts of the radionuclides could be ingested by some individuals.

The ratios SA/MPSA shown in Figure 1 change with size of detonation. This ratio for the thermonuclear reaction product, tritium, differs from the other radionuclides by increasing with size of detonation. The fission products decrease in ratio, SA/MPSA, by factors of about 25 with increase in energy yield of the explosive from 100 kt to 10 Mt. The same ratio for radionuclides from activated rock decrease by factors of about 5 through the increased yield range. Neutron-activated components of the device also decrease in SA/MPSA ratio with larger detonations, but do not follow consistent patterns.

Most of the calculations for environmental dilution of radionuclides in the present work are based on a 1 Mt detonation. Considerations of other size shots require corrections for total amount of radionuclide and the degree of initial isotope dilution. Shown in Figure 2 are the amounts of stable elements required to dilute the potentially hazardous radionuclides tritium, phosphorus-32, calcium-45, manganese-54, strontium-89, iodine-131, barium-140 and wolfram-185 to maximum permissible specific activities after deposition of fallout from devices ranging from 200 kt to 10 Mt explosive yield. Tritium from a 10 Mt detonation would require 50 times as much environmental dilution as from a 200 kt yield. This results from the production of 50 times as much tritium in the large explosive with essentially no isotope dilution from the vaporized rock, iodine-131 and barium-140 would also be subject to insignificant isotope dilution by the ejecta although the production of these, and other fission products would not change with explosive size. As a result, iodine-131 and barium-140 would require the same amount of isotope dilution in a 200 kt and a 10 Mt detonation. In contrast, strontium-89 and wolfram-185, both derived from the device, would undergo appreciable isotope dilution before ejection and would require decreasing amounts of environmental dilution by stable strontium and tungsten with increased size of detonation. Phosphorus-32, calcium-45 and manganese-54 would be produced mainly by neutron activation of the geological matrix in increasing amounts with increased explosive yield. Because vaporization of rock would not increase as rapidly, about twice as much environmental dilution by stable phosphorus, calcium, and manganese would be required for a 10 Mt as for a 200 kt detonation. Because only these eight radionuclides would require further dilution after ejection from the excavation, corrections for explosive yield may be calculated relatively easily from the curves shown in Figure 2.

Table 1. Radionuclides which would be ejected at specific activities greater than those allowed in man from the firing of a 1 Mt nuclear explosive for optimum cratering in granite. The days required for the radionuclides to decay to MPSA with no environmental dilution are shown. The amounts of environmental stable elements required to dilute the radionuclides to acceptable values are shown for varied conditions.

Nuclide	T 1/2 Days	SA / MPSA	Days to decay to MPSA. No environmental dilution	Gms of element to dilute to MPSA at		Gms of element in water of Gulf of San Miguel*	** Depth of sediment in Gulf of San Miguel required to dilute to MPSA at:		
				Time 0	30 days		Time 0, 1 Mt shot	30 days, 1 Mt shot	30 days, five 1 Mt shots
H^{3}	4470	$3.2x10^{6}$	$9.7x10^{4}$	$1.4x10^{15}$	$1.4x10^{15}$	$2.9x10^{15}$	0	0	7.4meters
Na^{24}	0.6	$3.0x10^{6}$	13	$1.2x10^{13}$	0	$2.9x10^{14}$	0	0	0
P^{32}	14.3	$1.3x10^{4}$	196	$8.5x10^{11}$	$2x10^{11}$	$2x10^{8}$	11cm	2.9cm	13cm
Ca^{45}	165	9.6	620	$1.4x10^{10}$	$1.2x10^{10}$	$1.1x10^{13}$	0	0	0
Ca^{47}	4.5	$3.3x10^{1}$	23	$5.1x10^{10}$	0	$1.1x10^{13}$	0	0	0
Sc^{47}	3.4	1.5	2.0	$1x10^{6}$	0	$2.3x10^{5}$	0***	0	0
Sc^{48}	1.8	$4.2x10^{1}$	9.7	$2.9x10^{7}$	0	$2.3x10^{5}$	0.03cm	0	0
Mn^{54}	314	5.2	754	$3x10^{8}$	$2.3x10^{8}$	$2.5x10^{7}$	0.02cm	0.01	0.05
Mn^{56}	0.11	$3.4x10^{5}$	2.0	$2x10^{13}$	0	$2.5x10^{7}$	0***	0	0
As^{76}	1.1	$8.1x10^{1}$	7	$1.1x10^{7}$	0	$6.8x10^{7}$	0	0	0
Br^{82}	1.8	$6.6x10^{1}$	4.9	$1.1x10^{7}$	0	$1.7x10^{12}$	0	0	0
Rb^{86}	18.7	1.4	9	$5.2x10^{7}$	0	$3.1x10^{9}$	0	0	0
Sr^{89}	50.4	9.5	165	$7.9x10^{8}$	$5.0x10^{8}$	$1.8x10^{11}$	0	0	0
Mo^{99}	2.3	$1.3x10^{2}$	16	$2.5x10^{7}$	0	$2.6x10^{8}$	0	0	0
Cd^{115}	2.3	3.3	4	$3.1x10^{4}$	0	$2.6x10^{5}$	0	0	0
I^{131}	8.1	$4.6x10^{4}$	126	$1.8x10^{9}$	$1.3x10^{8}$	$7.8x10^{8}$	20cm +	0	0
Te^{132}	3.2	$1.7x10^{1}$	13	$3.3x10^{5}$	0	$9.4x10^{5}$	0	0	0
Ba^{140}	12.8	$6.3x10^{1}$	77	$5.1x10^{9}$	$1.0x10^{9}$	$5.2x10^{8}$	0.2 +	0	0.15
W^{185}	75.8	4.8	167	$1x10^{6}$	$5.7x10^{5}$	$1.6x10^{6}$	0	0	0
W^{187}	1	$3.4x10^{2}$	8.4	$7.2x10^{7}$	0	$1.6x10^{6}$	0.9 +	0	0
Au^{198}	2.7	2.4	3.3	$2.2x10^{3}$	0	$2.6x10^{5}$	0	0	0
Pb^{203}	2.2	$2.7x10^{4}$	28	$5.4x10^{10}$	0	$7.8x10^{5}$	60+	0	0

* Only soluble-colloidal form included

** Assumes half of fallout falls into Gulf of San Miguel

*** Assigned no dilution because of very short half-life

\+ Shale values used

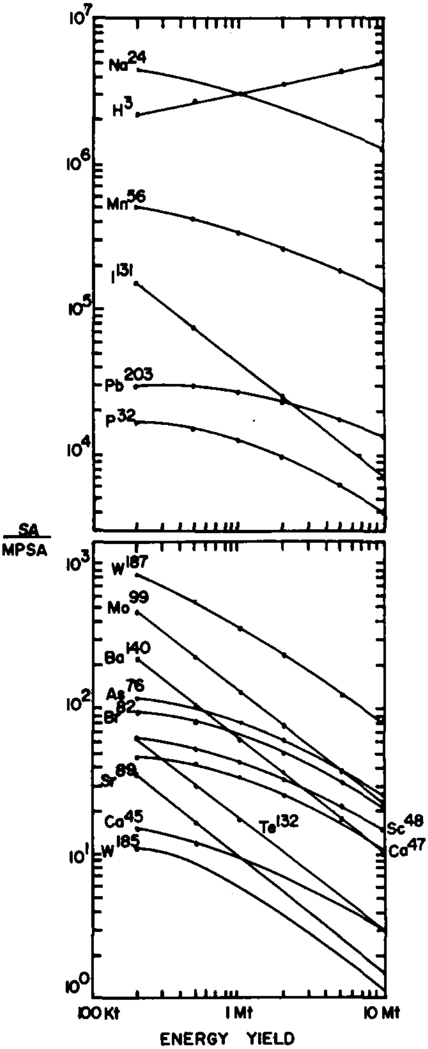

Figure 1. Ratio of specific activity to maximum permissible specific activity for radionuclides ejected from excavations at specific activities greater than those allowed in man. Based on the assumption that the radionuclides are mixed with vaporized rock.

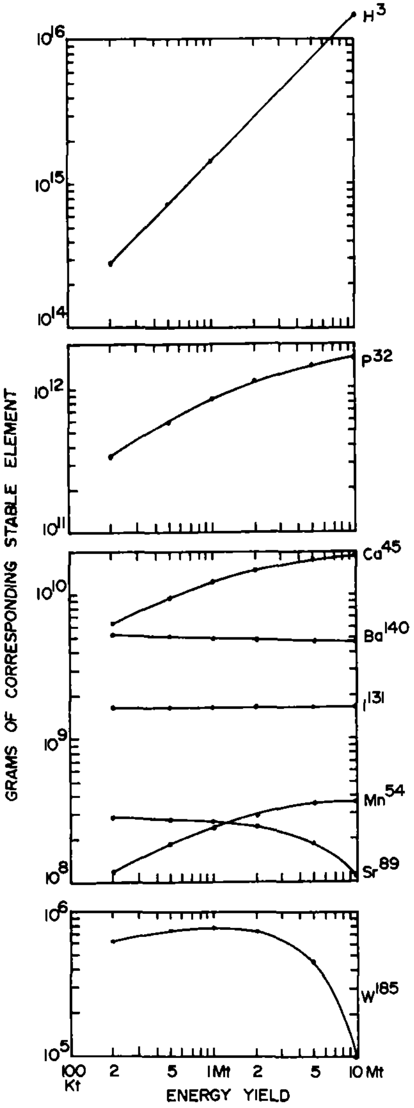

Figure 2. Grams of stable element required to dilute radionuclides in the fallout and cloud to MPSA for 200 kt to 10 Mt detonations in granite. For radionuclides requiring more than 11 weeks to decay to MPSA with no environmental dilution.

The interactions of tritium, phosphorus-32, calcium-45, manganese-54, strontium-89, iodine-131, barium-140 and wolfram-185 with the marine waters and their dissolved salts, colloids, particles and organisms are strongly dependent upon the area of introduction. Marine estuarine and open-sea regions are present on both the Atlantic and Pacific sides of the proposed canal sites in the Darien region of eastern Panama and the northwest corner of Colombia. In addition, a large semi-enclosed body, the Gulf of Panama, with seasonal upwelling, a year-round counter clockwise surface current and rich fisheries for shrimp and fish meal connects with the western terminus of Route 17, through the estuarine Gulf of San Miguel.

The surface circulation of the Atlantic and Pacific oceans in the vicinity of Panama and Colombia are subject to seasonal fluctuations (Figures 3 and 4). From January to April, the Doldrums move to the south and the dry northeast trade winds prevail in the Isthmian region. The dry season is a period of strong water currents in both the Pacific and Caribbean areas and marked upwelling of nutrient-rich deep water in the Gulf of Panama around the Pearl Islands. In late April or May the wind system moves northward and the Gulf of Panama is then influenced by the Doldrums and rain-bearing southwest winds. Upwelling ceases in the Gulf of Panama, the surface currents weaken, and the rainfall increases by a factor of 6 to 7 (Smayda, 1966). The total annual volume of fresh water entering the Gulf is 9.2×10^{10} m^3, an amount equal to 2.5 percent of the total volume of the Gulf or enough water to form a fresh-water layer 3.2 meters thick over the entire water surface. The greatest annual precipitation occurs over the San Miguel drainage basin, the site of Route 17. The net sea water flow in the Gulf of San Miguel results from river runoff although the Gulfs of Panama and San Miguel are subject to diurnal tides which range from 4 to 6 meters in height. These tides cause strong tidal currents, especially in the Gulf of San Miguel which resuspend and redistribute bottom sediments twice each day. In contrast, the maximum tidal excursion on the Caribbean coast is less than 0.76 m and this area receives only small amounts of runoff from Panama; however, the Gulf of Uraba receives large amounts of silt-laden water from the Atrato River in Colombia.

In summary, the Gulf of San Miguel, the near-shore areas of the Gulf of Panama and the Gulf of Uraba exhibit many characteristics typical of estuaries. The Pacific coast of Colombia and the Caribbean coast of Panama are "oceanic" environments. The Gulf of Panama is unique with its characteristic dry-season upwelling-water, which moves to the north of the Gulf before surfacing.

Estuarine areas differ from the open sea in several features which alter the relative influence of the water, organisms and bottom sediments upon radionuclide distribution. In the sea only limited sedimentation occurs. In contrast, relatively high rates of sedimentation are common in estuaries as a result of direct settling of suspended sediments, chemical precipitation, co-precipitation and sorption of fresh-water colloids to particles. These physicochemical reactions result mainly from the electrolytes of sea water interacting with the material introduced by rivers. Most of the sedimentary products are deposited on the bottom.

One of the estuarine areas which could receive significant amounts of high specific activity tritium, phosphorus-32, calcium-45, manganese-54, strontium-89, iodine-131, barium-140, and wolfram-185 is the Gulf of San Miguel. The distribution patterns and transport of these radionuclides would be determined mainly by their chemical characteristics which govern their interactions with the suspended sediments, the accompanying stable-element fallout and the bottom sediments. The radionuclides may be divided into two groups: (1) tritium, calcium-45, strontium-89 and iodine-131 would undergo little or no interaction with the dissolved, suspended and bottom material and would be subject mainly to physical dilution; and (2) phosphorus-32, manganese-54, barium-140 and wolfram-185 would be strongly sedimented by physicochemical mechanisms.

Tritiated water in fallout would rapidly mix with the water in the Gulf of San Miguel as a result of turbulence from tidal currents. If the worst possible case deposited 50 percent of the fallout tritium and other radionuclides into the Gulf, about 6 x 10^9 m^3 of water would be required to dilute the tritium to MPSA. The Gulf of San Miguel contains about 4 times this amount of water. The worst possible case assumes maximum venting of tritium from the excavation with all of the tritium as water and equal deposition of tritium and the other radionuclides in the area of fallout. Under actual conditions the deposition of tritium probably would be lower than that for the other radionuclides and its specific activity would decrease rapidly to levels below that allowed in man.

Other radionuclides which would be diluted to MPSA by the stable elements in solution in water of the Gulf of San Miguel are calcium-45, strontium-89, and wolfram-185. Thus, of the eight potentially hazardous radionuclides only phosphorus-32, manganese-54, iodine-131 and barium-140 would require additional isotope dilution (Table 1).

The radionuclides phosphorus-32, manganese-54 and barium-140 would be subject to rapid sedimentation in the Gulf of San Miguel. This estuarine area is fed by runoff from large watersheds drained by several rivers including the Tuira, Chucunaque, Sabana, Marea, Tucuti and Congo. During the wet season the watersheds receive large amounts of rainfall which remove organic and inorganic materials into the estuary, usually by channel erosion. The flooding rivers, entering the estuary, are unable to maintain their current velocities, except during ebb tides, and as a result drop much of their suspended sediments which sink at rates dependent on the mass and size of the particles. Upon mixing of the river water with the saline water of the estuaries the dissolved and colloidal iron, manganese, aluminum, titanium, zirconium, scandium and silica precipitate into hydrous gels because of the increased pH and electrolyte content of the water. Under these conditions colloidal clay particles also coacervate. Simultaneously, with the precipitation of the colloids, magnesium and calcium from the sea water provide limited exchange for some of the cations adsorbed to the suspended river sediments. Not all cations, however, are released

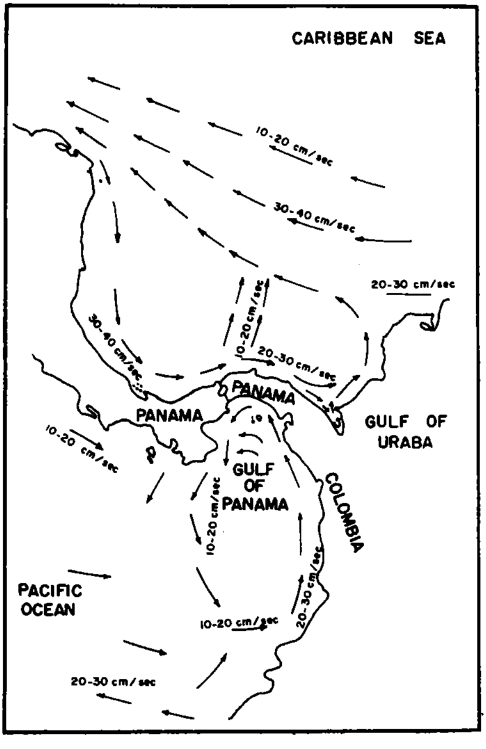

Figure 3. Surface circulation during the wet season in ocean waters off Panama.

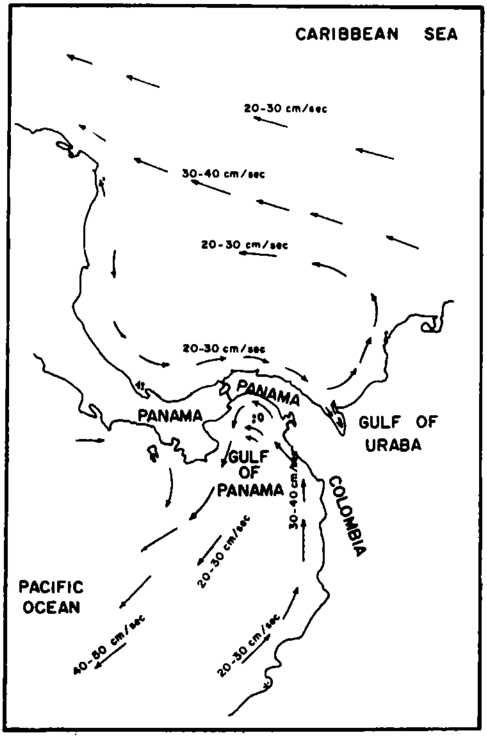

Figure 4. Surface circulation during the dry season in ocean waters off Panama.

by ion exchange. Zinc, cobalt, copper and ruthenium often are chelated to sediment particles in forms that cannot be desorbed by alkali or alkaline earth metals (Jones, 1960; Johnson, Cutshall and Osterberg, 1967).

Hydrated oxides of iron, manganese and aluminum may be termed "scavengers" because of their ability to remove ions from solution (Goldberg, 1954). The scavenging action of these gels is due largely to surface adsorption of ions with charges of opposite sign from that of the scavenger. The charge on ferric hydroxide gel in sea water is electropositive*--on hydrated oxides of manganese it is negative. Iron hydroxide, accordingly, should co-precipitate negatively charged ions and manganese oxides, positively charged ions. Under natural conditions, ferric hydroxide in sea water is found to concentrate multivalent ions of both charges. Muds, some organic particles and colloidal materials found in waters contaminated with radioactive fallout usually have positive surface charges and also are capable of adsorbing negatively charged ions (Amphlett, 1961; Rubentschik et al, 1936).

Phosphorus-32, manganese-54 and barium-140, added to estuarine regions, are rapidly co-precipitated and adsorbed to the surfaces of suspended and bottom sediments.** Approximately 90 percent of carrier-free barium may be removed from solution by ferric hydroxide and under natural conditions, where the precipitates may be formed slowly, more than 90 percent of the manganese may be incorporated into the precipitate.

Phosphorus-32 is rapidly adsorbed onto suspended organic and inorganic detritus and to bottom sediments. Pomeroy, Odum, Johannes and Ruffman (1967) observed that phosphorus-32, introduced into estuarine regions, was adsorbed quickly and locally near the sites of introduction and was not transported appreciably by water during short

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* According to Amphlett (1961) ferric hydroxide floc, when formed under alkaline conditions in fresh water, is negatively charged.

**Another radionuclide, lead-203, would be potentially hazardous the first week or two after fallout. Iron hydroxide and aluminum hydroxide effectively co-precipitate lead from alkaline solution (Gibson, 1961) and El Wakeel and Riley (1961) suggested that most of the lead sedimented from sea water is adsorbed onto ferromanganese minerals. According to Chow and Patterson (1962) about 99 percent of the particulate lead entering the oceans is sedimented from the sea water in shallow near shore regions. Krauskopf (1956) showed experimentally that lead was efficiently co-precipitated from sea water by ferric hydroxide and that it was also sedimented by adsorption onto clay minerals and organic detritus. This is in agreement with the observation that phytoplankton are able to concentrate lead by factors of 40,000 over the amounts in water. Revelle et al, (1955) suggested that hydrous manganese dioxide can co-precipitate lead from sea water.

periods of time. The radionuclide reached equilibrium between the water and sediments within 24 hours. In addition to being adsorbed to sediments phosphorus is almost quantitatively co-precipitated with ferric hydroxide gel. Sedimented phosphorus-32 does not remain permanently associated with the sediments. Pomeroy, Smith and Grant (1965) reported that the exchange of phosphate between the water and the sediment was controlled by two mechanisms: one an inorganic sorption reaction and the other controlled by biological exchange, probably between adsorbed micro-organisms and the water. In surface fractions of sediments poisoned by formalin, the rate of inorganic exchange of phosphorus was only 1/2 to 2/3 the rate of the inorganic plus biological exchange for sediments containing living micro-organisms. If bacteria compete on a like basis for other biologically important elements then they must exert a profound effect upon these trace elements in sediments.

Iodine-131 is not co-precipitated efficiently by hydrous oxide gels. Horma and Greendale (1959) tested co-precipitation of iodine-131 by ferric hydroxide but could only carry down 13 percent of the element. Iodine-131 was found by Gemmel (1952) to be 88 percent removed by bacterial and algal sewage sludge, and to subject to rapid turnover by the bacteria.

The co-precipitation of iodine by hydrated oxides of iron, manganese and aluminum would not be sufficient to reduce the specific activity to that allowed in man. Similarly, stable iodine in the water of the Gulf of San Miguel would supply only about 1/2 the amount required to reduce the specific activity to that allowed in man. Although iodine-131 would equilibrate rapidly with the stable iodine in the sediments, the mechanism would be of little practical value since it would be necessary for the radionuclide to equilibrate with the iodine in the sediments about 20 cm thick. A nine-day exclusion period would allow the radionuclide to decay to MPSA, however, after mixing with the stable iodine in the water. Although phosphorus, manganese, barium and lead would be almost quantitatively precipitated and sedimented to the bottom, only manganese-54 and barium-140 would be diluted to MPSA by the top centimeter of sediment shortly after time of fallout. Phosphorus-32 and lead-203 would require mixing with 11 and 60 cm depth of sediment to reach MPSA immediately after fallout. At 30 days after detonation phosphorus-32 would require mixing with about 3 cm of sediment and manganese-54 with 0.01 cm. All other radionuclides would have been reduced to specific activities lower than those allowed in man (Table 1).

All of the above calculations are based on a 1 Mt detonation in granite. In some instances a total yield larger than 1 Mt may be detonated at one time. If a total of 5, 1 Mt detonations were fired simultaneously and 1/2 of the total fallout was deposited in the Gulf of San Miguel, isotope dilution by the water would not be adequate to reduce the specific activities of tritium, phosphorus-32, manganese-54 or barium-140 to MPSA at 30 days post-shot. If tritiated water were deposited in the fallout at the same efficiency as the other fallout material the specific activity of tritium in the Gulf of San Miguel 30 days post-shot would be about 2-1/2 times that allowed in man. As stated before, the deposition of tritium in the immediate fallout may be expected to be lower than that for other radionuclides and the specific activity in the marine waters would be lower than indicated above. Phosphorus-32, from the 5 detonations, would require mixing with only 13 cm of bottom sediment to be diluted to MPSA. Manganese-54 and barium-140 would be diluted to acceptable values by 0.05 and 0.15 cm of bottom sediments respectively. It thus appears that with the possible exception of tritium the radionuclides from the simultaneous firing of 5 1 Mt explosives would not provide significant hazards to humans in the Gulf of San Miguel after 30 days following detonation.

Probably one of the most critical marine areas for fallout at least in regards to fisheries--is the Gulf of Panama. Sedimentary processes would also operate in this region because of (1) the twice daily resuspension of the near-shore bottom sediments by tidal currents; (2) the finely-divided precipitates of iron, aluminum, manganese, silica, titanium and zirconium supplied by rivers; (3) the particulate organic detritus which, at times may equal the amounts of suspended sediments and (4) the stable fallout elements. In addition to sedimentation, wind driven surface currents and the upwelling of deep currents in the northern part of the Gulf during the dry season, would result in significant dilution and transport of water out of the Gulf into the open ocean. Dilution and transport from the Gulf of Panama would also occur during the wet season but would not be as pronounced as during the dry season.

The Gulf of Panama is approximately circular in shape and has an area of 28,850 Km^2, the maximum dimensions being 175 Km in a north-south direction and 245 Km in an east-west direction. The waters are relatively shallow with 91.4 percent of the Gulf being less than 200 meters deep. The total volume of the Gulf of Panama is about 2.1 x 10^{12} m^3.

Figures 4 and 5A show the main features of the Gulf of Panama during the dry season. The Colombia Current flows north along the Pacific Coast of Colombia at velocities of 30 to 40 cm per second and divided into two parts in the area of the Pearl Islands with the major portion flowing west across the mouth of the Gulf of Panama and a smaller portion flowing counterclockwise north of the Islands. As the current exits from the Gulf of Panama it joins the current coming across the entrance and flows southwest into the Pacific Ocean. This current pattern appears to influence the distribution patterns of those stable elements which rapidly precipitate upon addition to sea water from river outflows. Just south of, and in the entrance to, the Gulf of San Miguel, enhanced amounts of iron, scandium and

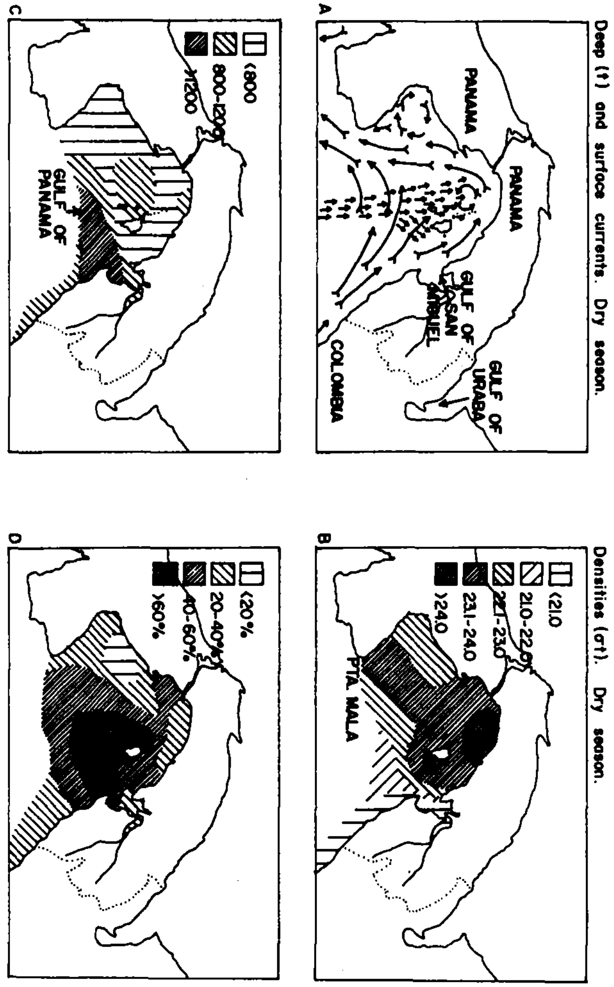


Figure 5A. Surface currents (→) and deep currents (↑) showing the flow of deep water toward the north of the Gulf of Panama where upwelling occurs. Figure 5B. Water densities (σt) in the Gulf of Panama. The two areas of high density (σt > 24) are sites of upwelling. Figure 5C. Distribution of stable manganese in bottom sediments of the Gulf of Panama and the Gulf of San Miguel. Figure 5D. Distribution pattern of the percent extractable stable manganese in bottom sediments of the Gulf of Panama.

manganese occur in the bottom sediments (Figure 5C) and for all of these elements, larger fractions of the total amounts may be extracted from the sediments toward the center of the Gulf of Panama (Figure 5D). These extractable fractions probably represent, mainly, iron, scandium and manganese precipitated from river additives. Fallout, co-precipitated by the hydrous oxide precipitates would also tend to be concentrated in the sediments of the same area.

The upwelling that occurs in the Gulf of Panama during the dry season contributes significantly to the circulation in that body of water. The deep water currents which upwell in the northern part of the Gulf are shown in Figure 5A and the area affected by upwelling is shown in the surface-density diagram (Figure 5B). The increased densities indicate the areas of upwelling.

The volume flow, per second, of the currents in the Gulf of Panama, may be calculated by multiplying the cross-sectional area of the current by its average velocity at right angles to the cross-section plane. The results of these calculations are as follows:

Current	Width in Meters	Depth in Meters	Average Velocity m/sec	Volume of Flow m^3/sec
Colombia Current	1.6×10^5	50	0.175	1.4×10^6
Entering Gulf of Panama	4.0×10^4	20	0.125	1.0×10^5
Leaving Gulf of Panama	5.0×10^4	20	0.175	1.7×10^5

Only about 7 percent of the water in the Colombia Current flows into the Gulf of Panama and an excess 7×10^4 m^3/sec of water flows out of the Gulf of Panama in excess of that flowing into it. The source of this water is to be found in the upwelling reported by Smayda (1966), Forsbergh (1963) and Schaefer et al, (1958). The area of upwelling (Figure 5B) comprises about 1/8 of the surface area of the Gulf of Panama and would result from an average upward flow of deep nutrient-rich water of about 1.7 m/day. In the area of upwelling the added water equals about 70 percent of the volume added through surface flow of the Colombia Current.

Because the surface and deep currents do not travel in the same direction a shear zone exits at their boundaries. A model of physical (and isotope) dilution may be made using simplified assumptions as follows:

1. All significant mixing takes place in the upper mixed layer.

2. Vertical mixing in the mixed layer occurs in less than 24 hours.

3. Vertical mixing through the thermocline is slow and for the purposes of the calculations may be considered negligible.

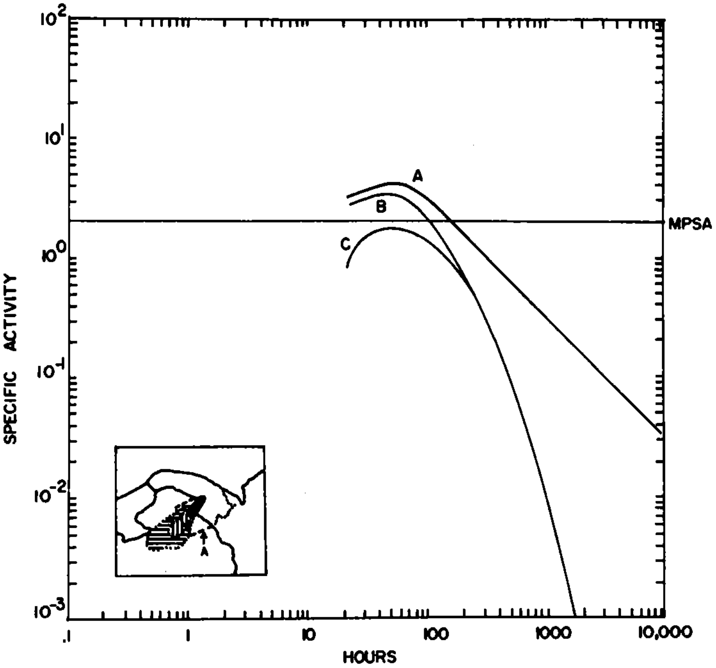
4. The vertical distribution of current velocity ranges from zero at the upper edge of the thermocline to a maximum at the surface. Analogue and digital models of mixing were developed and were applied to specified conditions of fallout in the Gulf of Panama.

In addition to physical mixing, corrections were made for biological delay of radionuclides moving through food chains to man. A mathematical model was developed in which it was assumed that an initial specific activity of zero in an organism for any radionuclide will come to equilibrium with the environment after a given period of time, dependent upon the biological half-life and the increase of activity in the food. Neglecting isotope effects, the specific activity in the organism can never exceed the specific activity in the environment. The calculation of the delay which a particular organism experiences in coming to a maximum specific activity is thus a calculation of the rate at which the organism achieves equilibrium with its environment. Plankton were assumed to equilibrate with sea water in less than 24 hours. Thus, the plankton and sea water were considered as one unit in all calculations. The Gulf of Panama was divided into four areas based upon commercial fisheries. Area "A" is shown in Figure 6.

The worst possible case for the deposition of fallout from a one Mt detonation in the Gulf of Panama would occur if the entire fallout pattern were deposited in the confines of the Gulf. This would also constitute the worst possible case for the Gulf of San Miguel. The results of the calculations for iodine-131 in the area of heaviest fallout in the Gulf of Panama are shown in Figure 6. Although the specific activity of the radionuclide in the water exceeded MPSA for man, the specific activities in the molluscs, crustaceans and fish remained below MPSA because of biological delay. Similar calculations for tritium showed that the specific activity in the water or food organisms of man would not exceed MPSA.

If the specific activities in food organisms are calculated as shown above, and the amount of stable element per unit live-weight of organisms is derived from analyses of organisms collected in the area of interest, the amounts of the radionuclide in μCi per unit live-weight may be calculated. Thus the results of the analyses and calculations may be applied in cases where the concentrations of radionuclides have been calculated on a maximum permissible concentration basis for foods from a wide variety of sources or in cases where the limitations on food utilization are based on the maximum permissible specific activities allowed in the critical organs of man.

Figure 6. The calculated specific activities of water (A and B) and molluscs, crustaceans and fish (C) in an area of the Gulf of Panama receiving the heaviest concentration of fallout from a one Mt detonation.



Section A, I^{131}

A **Physical dilution**

B **Physical dilution plus radioactive decay**

C **Specific activity in mollusc and crustacean soft parts, and fish muscle**

REFERENCES

1. Amphlett, C. B. Treatment and Disposal of Radioactive Wastes, Pergamon, Lond. (1961)

2. Boardman, C. R., D. D. Rabb and R. D. McArthur. AEC TID 7695 (1964).

3. Chow, T. J. and C. C. Patterson. Geochim et cosmochim, Acta 1962, 26:263.

4. El Wakeel, S. S. and J. P. Riley. Geochim. et cosmochim, Acta, 1961, 25:110.

5. Forsbergh, E. D. InterAmer. Trop. Tuna Comm., 1963, 7:1.

6. Gibson, W. M. NAS-NS 3040 (1961).

7. Goldberg, E. D. J. Geol., 1954, 62:249.

8. Honma, M. and A. E. Greendale. Engr. Chem., 1959, 51:697.

9. Johnson, V., N. Cutshall and C. Osterber. Water Resourc. Res., 1967, 3:99.

10. Johnson, G. W., G. H. Higgins and C. E. Violet. J. Geophys. Res., 1959, 64:1457.

11. Johnston, R. J., J. Mar. Biol. Ass., U. K., 1964, 14:87.

12. Jones, R. F. Limnol. Oceanogr., 1960, 5:312.

13. Krauskopf, K. B. Geochim et cosmochim, Acta, 1956, 9:1.

14. Lowman, F. G., R. F. Palumbo and D. J. South. AEC UWFL-51 (1957).

15. National Academy of Sciences-National Research Council. The Biological Effects of Atomic Radiation, Summary Report, A/AC.82/GL-358 (1960).

16. Ng, Y. C. AEC UCRL-14249 (1965).

17. Nordyke, M. D. and M. M. Williamson. AEC PNE-242F (1965).

18. Pomeroy, L. R., E. P. Odum, R. E. Johanes and B. Roffman. Int. Symp. Disp. Radioact. Wastes into Seas, Oceans and Surface Waters, IAEA (1966).

19. Pomeroy, L. R., E. E. Smith and C. M. Grant. Limnol. Oceanogr., 1965, 10:167.

QUESTIONS FOR FRANK G. LOWMAN

1. From Walt Kozlowski:

Your study of the Panama Zone seems impressive indeed. In view of all you know, do you consider a nuclear generated panama sea-level canal feasible from a safety viewpoint to man? - to marine environment?

ANSWER:

The Panama Canal Commission should answer this, but I guess I could give my personal opinion. With proper controls, I think that the radioactive contamination problem would not keep the canal from being built. There is to be control over fisheries and control over movement of people, but as far as radioactivity, I don't think there is a problem there.

2. From M. E. Wrenn:

Your estimate for production of iron-55 relative to manganese-54 appeared low to me when compared for example with amounts detected from the weapons tests in 1962. Are your estimates of iron-55 production realistic and what is the basis of the estimate?

ANSWER:

The basis for these estimates is the Warner Report, the guideline given to us by the AEC. I don't know if I want to comment on that. I work with the numbers that are given me. This is all I can do in this case. I think that they are close enough that the errors that would occur would not greatly change the results that we came up with.

3. From J. Cohen:

How would you compare your MPSA approach with that of Fleming's MER?

ANSWER:

I think this approach is similar to one Dr. Fleming had before and our numbers came out pretty close, although we don't agree at all on the basis for arriving at our numbers. I have to look at this one more closely before I can see how they do - whether they do agree or not. If I may I would like to make a short statement on this cesium thing. We studied cesium in the soil at the Eniewetok test site where there are large amounts of rain and many tropical areas. Anyway in that area, the cesium was taken up very highly compared to strontium-90 and the reason was that there is a very short potassium shortage in the soil and some of the plants couldn't get enough otassium and so they were taking up cesium instead. One way to prove that there was a potassium shortage was to take a bottle of potassium chloride solution and a paint brush and paint stripes on the leaves of the plants as we went by and three days later there was a very bright green stripe where we painted the potassium on. There is a definite potassium shortage in some tropical areas.

AEC CONTROLLED AREA SAFETY PROGRAM

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ABSTRACT

The detonation of underground nuclear explosives and the subsequent data recovery efforts require a comprehensive pre- and post-detonation safety program for workers within the controlled area.

The general personnel monitoring and environmental surveillance program at the Nevada Test Site are presented. Some of the more unusual health physics aspects involved in the operation of this program are also discussed.

The application of experience gained at the Nevada Test Site is illustrated by description of the on-site operational and safety programs established for Project Gasbuggy.

* *

The general theme of this symposium is directed toward the public health aspects of the Plowshare program where public is in the context of non-program related residents living outside the test or project area. The health and safety of the workers within the on-site or controlled area are of equal concern to the Atomic Energy Commission.

For a better understanding of the operations at the Nevada Test Site (NTS), some knowledge of the site is necessary.

The first slide (Figure 1) shows the NTS and the general area around the NTS. The Nellis Air Force Range is closed to the public and therefore provides to some extent a buffer zone between test activities and the general public.

The next slide (Figure 2) shows the NTS proper. The site is located in Nye County about 65 miles northwest of Las Vegas. The main entrance to the site is at Mercury which contains the base camp with offices, laboratories, warehouses, living quarters, and recreational facilities for the workers who live there.

To the north of Mercury are the Frenchman and Yucca Flat areas. These were the primary testing areas for atmospheric detonations prior to the signing of the Limited Nuclear Test Ban Treaty. These areas are now used for underground testing in vertical holes with the bulk of the tests being conducted in Areas 3, 7, 9, 10, and 2. From the center of the forward test areas in Yucca Flat, it is some forty miles to the nearest off-site permanent residence.

The main control point is located midway between the Yucca and Frenchman Flat areas.

Area 12 contains the main tunnel complexes. These tunnels are mined into the side of Rainier Mesa to give larger work areas for more complex experiments than can be placed in the vertical holes.

Pahute Mesa provides facilities for testing at higher yields than are feasible in Yucca and Frenchman Flats.

The Nuclear Rocket Development Station is set aside for the testing of nuclear engines for rocket vehicle application.

Several nuclear excavation experiments have been conducted at the NTS, among them the Sedan event in Area 10, Buggy in Area 30, and the Cabriolet, Palanquin, and Schooner events in Area 20.

Before describing radiological safety procedures, a few words should be said about how releases of radioactive effluent at detonation time can occur in nuclear explosives testing. Since the signing of the Limited Nuclear Test Ban Treaty, all United States nuclear explosives tests have been conducted in an underground environment. The majority of the tests conducted since the treaty have been designed to be fully contained (that is, release no radioactivity to the atmosphere). Only in the case of such things as excavation or aggregate production-type experiments is any release of radioactive effluent at detonation time anticipated and even in this case the fraction of radioactivity released is designed to be small compared to the total amount of radioactivity produced.

For experiments designed to be fully contained it must still be recognized, however, that some radioactivity can be released by accident. Such releases are customarily separated into two rather loose categories referred to as "venting" and "seepage." Venting can be roughly defined as a prompt release of radioactivity usually occurring within a few minutes after the detonation and frequently resulting in a visible and radioactive dust cloud. Seepage may also start shortly after detonation but usually does not produce a visible cloud. It is characterized by a low-level, long-term release of highly fractionated fission products consisting primarily of noble gases and volatiles. The few ventings which have occurred, on the other hand, have generally been relatively unfractionated and have lasted for only a very short period of time. Causes of these effluent releases are not always readily determined. Seepage has been bound to occur through firing and diagnostic cables leading to the explosive, through fissures in the soil, or in and around the emplacement casing where stemming or grouting material has been shifted by the detonation.

Causes of ventings are even more difficult to determine than for seepages. It appears, however, that such things as shallow burial and local weaknesses in the geological medium can combine to produce ventings.

With this rather sketchy background, the more unusual portions of the on-site health protection program can be described. The industrial safety, fire protection, and medical problems encountered in testing programs are typical of the heavy construction and drilling industries and will not be discussed here.

At the present time the Nevada Operations Office has two contractors who provide on-site radiological safety services. At the Nevada Test Site the Reynolds Electrical and Engineering Company (REECO) provides these services. At sites other than the NTS our contractor is the Eberline Instrument Corporation. The services which both contractors provide are basically the same.

Each contractor maintains an active on-site environmental surveillance program, provides training as necessary, and controls and documents any radiation exposures to on-site workers by use of personnel dosimetry and bioassays.

Because some of the health physics problems which are encountered are unique to nuclear explosives operations, and particularly to drilling and tunneling operations, it is necessary that monitoring personnel receive at least a portion of their field experience working on drill rigs and in tunnels.

Prior to each test, air sampling units and remotely operated gamma exposure rate measuring units are placed around the surface ground zero. These units document any release of radioactive effluent. In addition, the exposure rate units which comprise what is more commonly referred to as a remote area monitoring system (or RAMS) provide an early indication of any release and can provide information on exposure rate levels at stations where re-entry is required. The RAMS units in current use normally have a six-decade readout capability from about one mR/hr to 1,000 R/hr. The output of these units is returned by hardwire or r-f telemetry to the control point for evaluation by the Test Manager and the testing laboratory. Should a release of radioactive effluent occur, standard procedures have been developed for estimating the quantity of radioactivity released to the atmosphere based on meteorological conditions and an assumed source geometry.

This equipment is, of course, installed, checked out, and calibrated well prior to the detonation.

Based on the meteorological and maximum credible radiation predictions presented at the first pre-shot weather briefing, areas around the immediate test area are cleared of all personnel not necessary for the final pre-shot preparations. Additional weather briefings prior to detonation time may expand or shift the areas to be cleared of personnel.

For tests which are predicted to cause significant motion from seismic effects, personnel may also be removed from tunnel or underground work areas, drill rigs may be shut down, and personnel generally required to be in non-precarious locations.

Prior to the event, geophones which monitor seismic activity are also placed in the vicinity of the surface ground zero. After the event, these geophones monitor the progress of the underground chimney as it works its way toward the ground surface. Personnel are kept outside the surface ground zero area until a surface subsidence occurs or until the geophones indicate the underground growth of the chimney is complete.

Following the detonation, and after geophone and RAMS readings indicate it is safe to re-enter the test area, an initial radiation survey is made of the detonation site. Monitoring personnel are equipped with anti-contamination clothing and respiratory protection equipment. The radiation survey includes the emplacement casing, any instrument holes, cables, and the diagnostic or timing and firing trailers. The radiation survey data is relayed to the control point, recorded, and evaluated. As soon as the evaluation has established that there are no significant radiological hazards, scientific personnel are permitted to re-enter to recover their data and equipment. For those rare cases where a radiological problem exists, monitors are provided for each recovery party to assure that they do not exceed permissible exposure standards. In such a case, scientific personnel are also appropriately dressed in anti-contamination clothing and provided with respiratory protection.

Prior to the detonation a radiological safety check station is established at the re-entry point to control personnel access and to assure that re-entry personnel are appropriately outfitted. Should a radioactivity release occur, personnel and equipment are monitored upon exit from the area and can be given preliminary decontamination at this check station if necessary.

Under normal conditions for those events designed for containment, no radiation problems exist and the check station or access control trailer is moved to within a thousand feet or so of surface ground zero as soon as the initial surveys and data recoveries are completed. Movement of the check station to a location close to the emplacement site reduces the size of the area under control and permits resumption of normal operations in those areas outside the immediate emplacement site.

Following the detonation it is normally necessary to re-enter the detonation zone (usually by drilling) to obtain samples of the radioactive debris. These samples are used for determination of explosive yield and for other diagnostic information.

The next slide (Figure 3) shows three methods of post-shot drilling used at the Nevada Test Site.

The next slide (Figure 4) depicts a general circulation system of the drilling fluid for the drill rig. This fluid circulates from a pump through a hose to the drill stem. It then flows down the drill stem and out through the drill bit thereby cooling and lubricating the bit. The fluid then returns to the surface through this annulus carrying the cuttings in suspension. Since several drilling fluids may be used such as mud, water, air (and in the case of gas fields, natural gas), the treatment at this point depends on the fluid used. At the NTS some form of mud is customarily used for post-shot drilling.

As drilling proceeds, a point is reached where circulation of the drilling fluid is lost. This is desirable since, if circulation is not lost, radioactive mud can be returned to the surface as the drilling nears the radioactive melt zone. Circulation is lost because the fluid flows out into the fractured zone near the detonation point.

In some cases radioactive gas, or radioactivity contained in steam produced by the fluid contacting the thermally hot detonation zone, forces its way to the surface through the annulus or drill stem. To reduce effluent releases to the atmosphere and minimize personnel exposures from this source, several treatment methods are available. One method consists of making this a closed system so that material returned to the surface is placed back down the hole. For cases where this method is not practical, the fluid or gases can be run through a ventilation system consisting of mud or chip traps, a charcoal filter system, and released to the atmosphere. This system removes essentially all radioiodine from the effluent so that for practical purposes only the noble gases are released. Quantities of radioactive effluent released are such that they are seldom detectable outside the immediate work area.

Personnel are assigned for radiation monitoring on and around the drill rig during the re-entry. At the same time air samplers and RAMS units are set up around and on the rig ventilation system to measure and document any release of radioactivity.

The next slide (Figure 5) shows one method of obtaining a sample of the radioactive debris. A coring tool is lowered on a wire line into the center of the drill string and forced out into the hole wall.

The coring tool is then raised to the surface with the sample wedged inside. At the surface radiation monitoring personnel remove the sample from the tool and package it for shipment to the laboratory sponsoring the test.

After recovery of samples, the post-shot sampling hole is sealed off, the drill rig and tools are decontaminated if necessary, and any radioactive waste is cleaned up.

Procedures similar to those described are used on almost all nuclear explosive tests regardless of whether they are conducted for weapons testing or Plowshare. Specific procedures will vary somewhat from event to event, depending on the type and purpose of the experiment and individual circumstances.

To show specific application of some of these procedures, the next slide (Figure 6) shows the exterior of the access control trailer used for Project Gasbuggy. Note the cribbing and tiedowns for protection of the trailer against ground motion.

One view of the interior of the access control trailer is shown in the next slide (Figure 7). The bins and cabinets are used for storage of protective clothing, spare parts, and miscellaneous equipment. Not visible in this view are a large hot water tank, sink, and shower for personnel decontamination.

The next slide (Figure 8) shows the Gasbuggy RAMS array used on the day of detonation. Note that on this particular event two units were placed in the downhole stemming. This procedure gives an early warning should radioactive effluent begin to work its way up through the stemming.

The final slide (Figure 9) shows the RAMS array used for the postshot drilling. The Gasbuggy nuclear explosive was placed in the 20-inch diameter emplacement hole by lowering the explosive on the end of a 7-inch diameter drill string. Stemming was then placed inside the 7-inch string and in the annulus between the 7-inch string and the 20-inch casing.

The initial re-entry into the Gasbuggy chimney was made by drilling with natural gas to a depth of about 3,260 feet at which point the drilling fluid was changed to a water-bentonite mixture because of wet-hole conditions and cement buildup on the drill pipe. Four RAMS units were placed on a circle of about 300-foot radius around the emplacement hole.

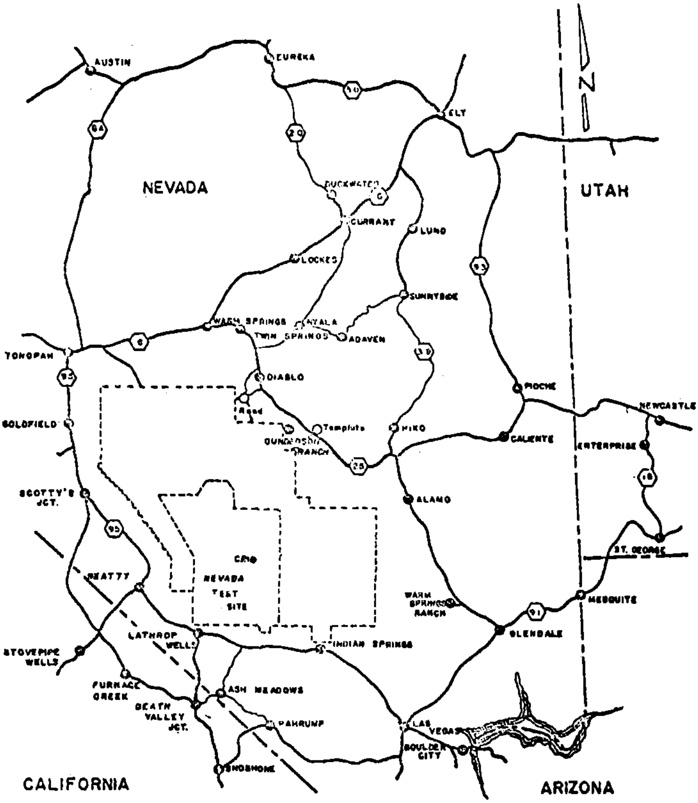
For that portion of the drilling which used natural gas as a drilling fluid, a gamma ray scintillation detector was placed on the exhaust line to detect any release of radioactivity in the gas. For that portion of the drilling which used the water-bentonite mixture, RAMS units were placed on the mud line and on the mud storage tank. The data from the downhole RAMS units and from other detectors mounted below the rig floor were also available.

In addition to the equipment shown, an air sampling array was established for zero time with equipment and facilities available for calibration, maintenance, and repair of electronic equipment as well as a mobile sample analysis laboratory.

Sample of the drilling fluid returns were collected and analyzed in these facilities as well as the usual air, soil, water, and vegetation samples.

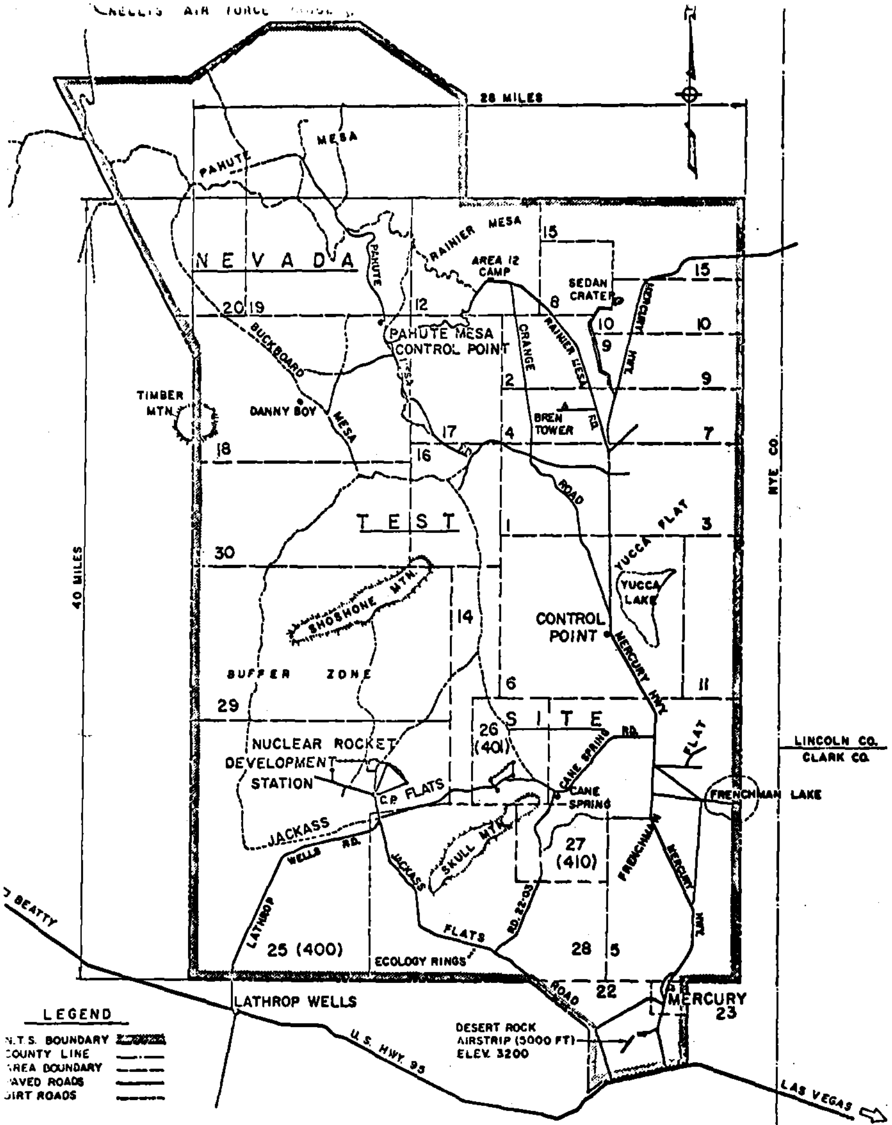
The maximum radiation exposure of any on-site worker for the Project Gasbuggy detonation and subsequent post-shot drillback was less than 10% of the maximum permissible guidelines for the experiment.

In summary, the general Nevada Test Site radiological safety and documentation program is readily adaptable for use on Plowshare experiments conducted at sites other than NTS and will provide adequate control of employee radiation exposures.



SOUTHERN NEVADA AND NEVADA TEST SITE VICINITY

FIGURE NO. 1

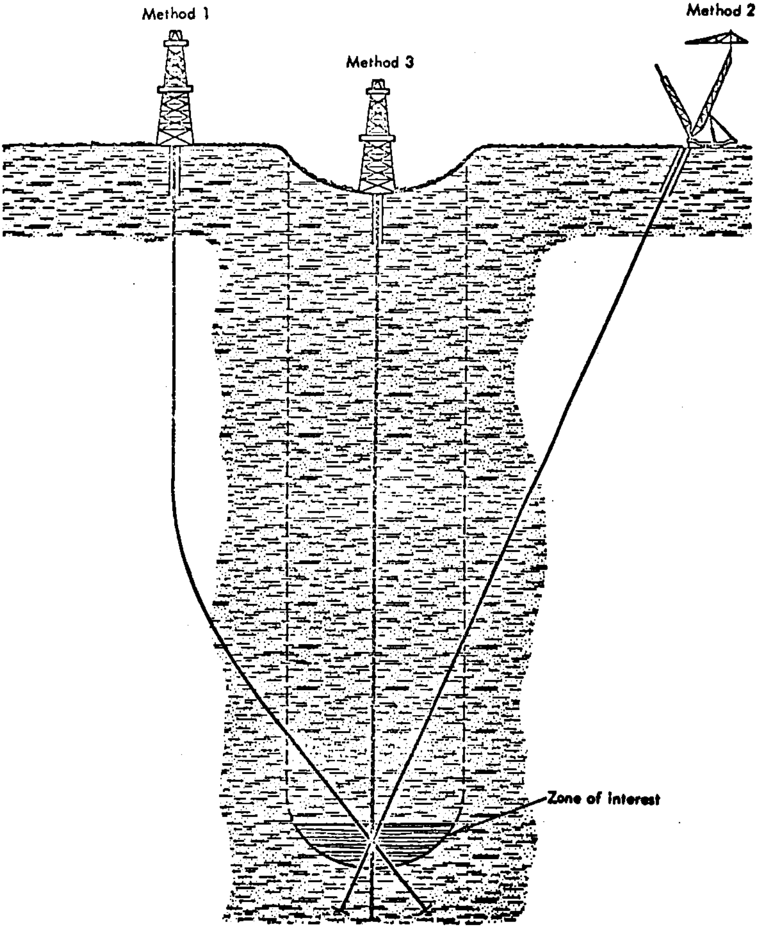


NEVADA TEST SITE

GRAPHIC SCALE

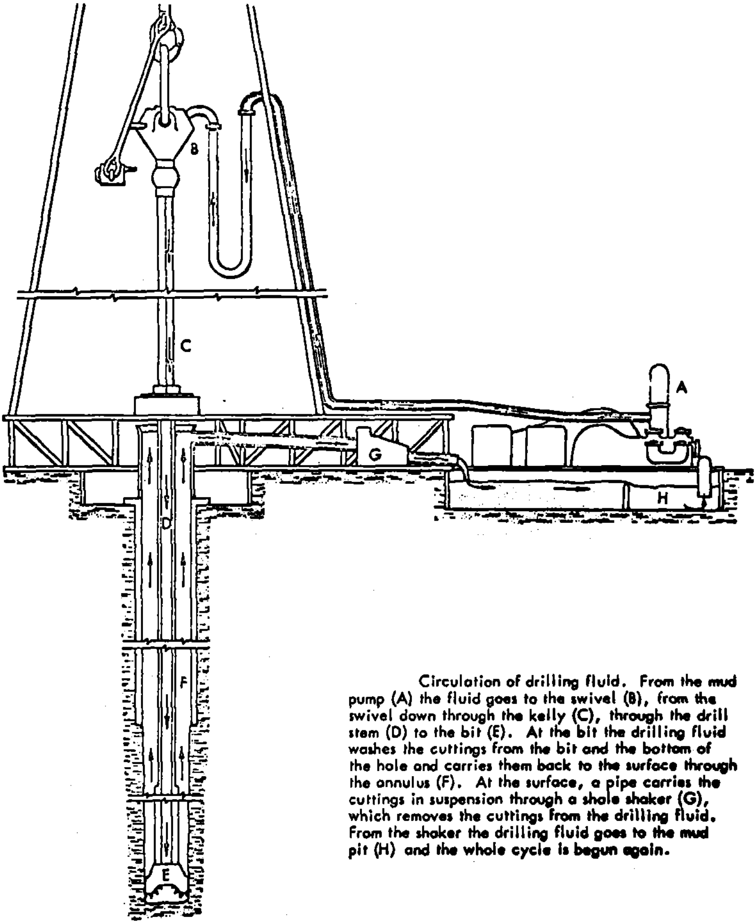
5 0 5 MILES

Figure No. 2



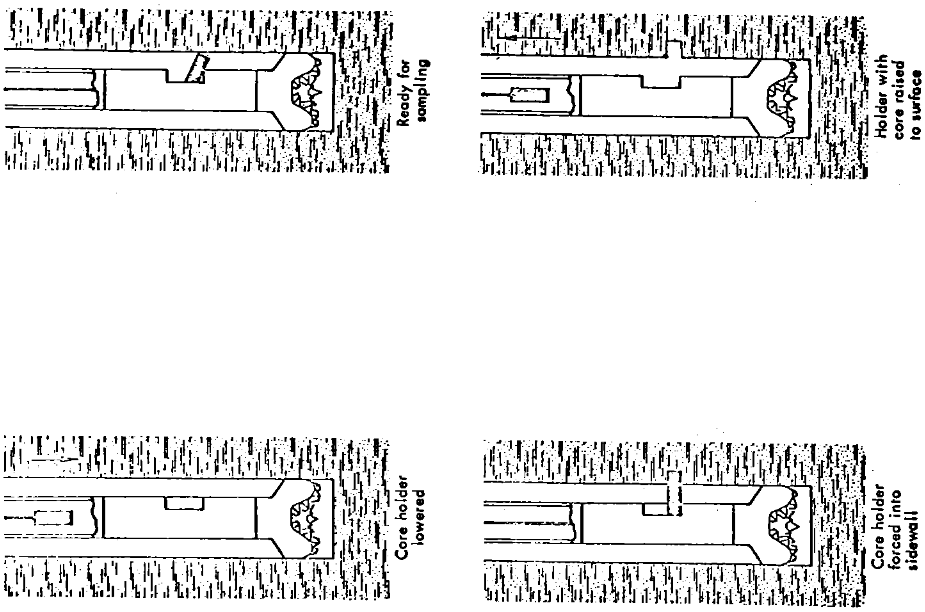
Three methods of postshot drilling at NTS.

FIGURE NO.3



Circulation of drilling fluid. From the mud pump (A) the fluid goes to the swivel (B), from the swivel down through the kelly (C), through the drill stem (D) to the bit (E). At the bit the drilling fluid washes the cuttings from the bit and the bottom of the hole and carries them back to the surface through the annulus (F). At the surface, a pipe carries the cuttings in suspension through a shale shaker (G), which removes the cuttings from the drilling fluid. From the shaker the drilling fluid goes to the mud pit (H) and the whole cycle is begun again.

FIGURE NO. 4



Four steps in taking a sidewall sample.

FIGURE NO. 5

Figure 6: OUTSIDE VIEW OF ACCESS CONTROL TRAILER

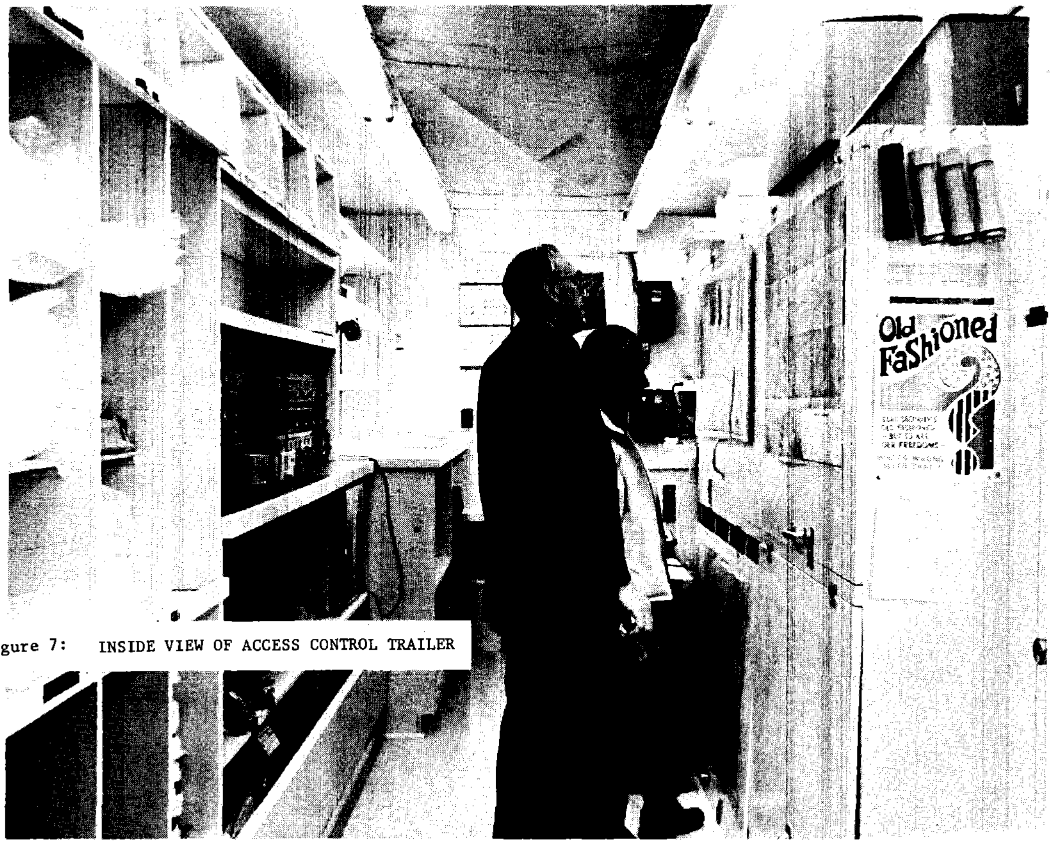


Figure 7: INSIDE VIEW OF ACCESS CONTROL TRAILER

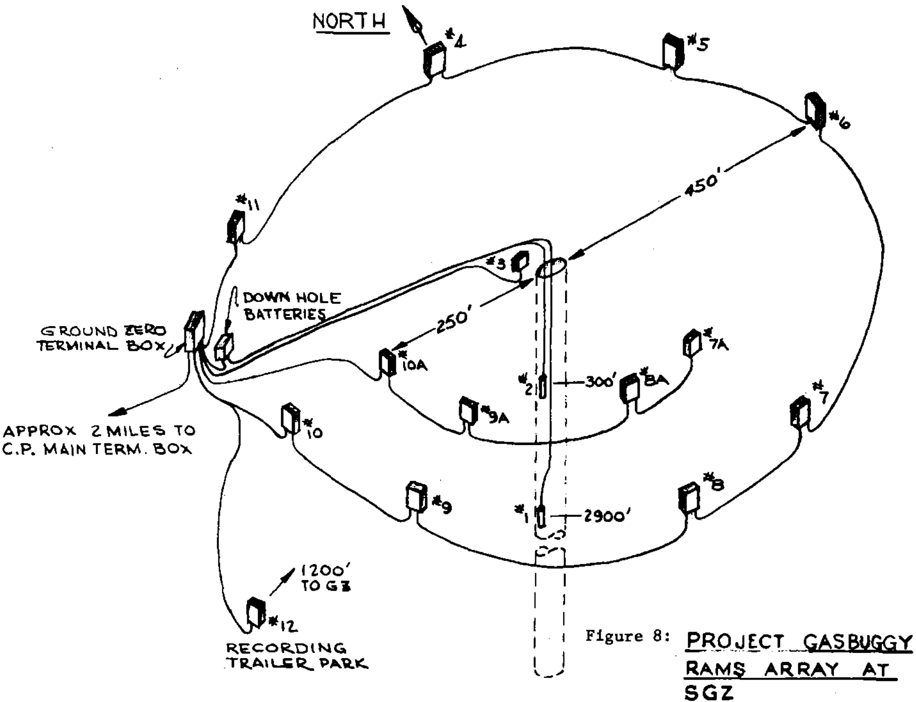


Figure 8: PROJECT GASBUGGY RAMS ARRAY AT SGZ

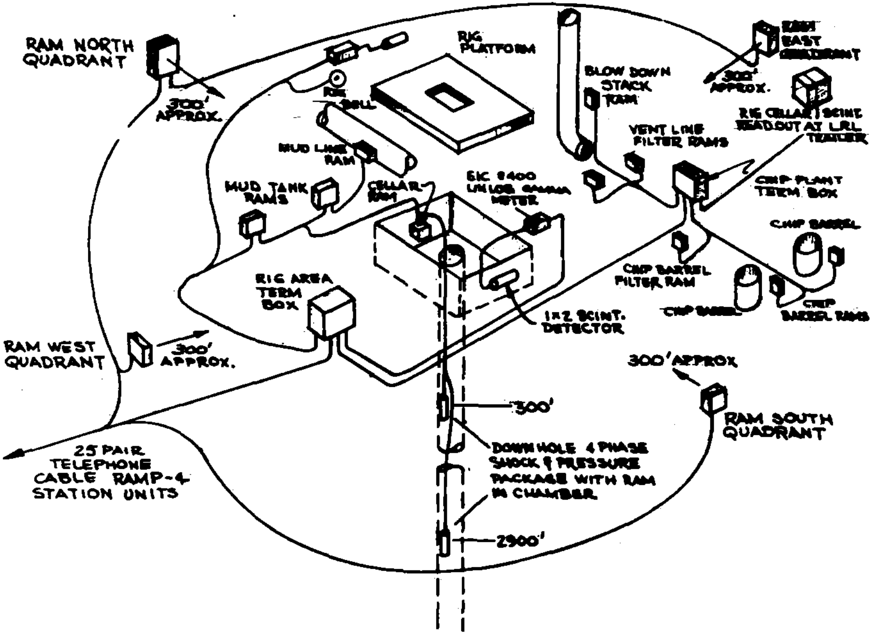


Figure 9: PROJECT GASBUGGY RAMS ARRAY FOR POST SHOT DRILLING

QUESTIONS FOR DONALD HENDRICKS

1. From Tom Rozzell:

   How long is monitoring for seepage continued after each shot?

   ANSWER:

   As long as necessary, sometimes the seepage has lasted for a few hours and other times it has lasted for a number of days. We try to monitor it until we are sure that it has stopped. I should mention that in some cases we are able to stop these seepages. It depends strictly on how they occur. If it is coming through the stemming inside the emplacement casing, we are able to put cement or something in there to try and stop it. If it's leaking from just broken ground or a crater, stopping it is not always possible. You can pour a cement pad over it and it will continue to leak around the edges and we will monitor it as long as it is seeping.

2. From Robert Karsh:

   Under your definition of a "contained" detonation, how much gaseous radiation release is permissible before you conclude the detonation was not contained?

   ANSWER:

   We, on occasion, have small releases as mentioned before from cables around the emplacement hole - in general they range from a few curies and by few I mean a few 10's to 100 curies or so and my personal opinion is that they are satisfactorily contained. They are not, in general, detectable outside the immediate ground zero area.

3. From Sidney Porter:

   You stated that a total of 10% of Gasbuggy allowed exposure was the maximum. What was this allowed exposure and how was the actual exposure measured?

   ANSWER:

   The guidelines which were used, and note I am addressing myself only to on-site workers here, the guidelines are those which are contained in AEC Manual, Chapter 0524 and are essentially similar to those contained in Part 20 with minor differences, but in this case it's three rem per year external exposure, five times N-18 and the rest of that. I didn't bring the exact numbers, but these are measured from film badges, pocket dosimeters and that sort of thing. There was also a urinalysis done on those people for whom any internal exposure of tritium was suspected.

4. From Robert Karsh:

A radioactive nature lover from Las Vegas recently tripped the monitoring device at Kennedy airport with dust in his pants cuffs. Does this imply excessive distribution of vented radiation?

ANSWER:

Well, I would like to know the details on the story. We heard the same rumor and checked it out and the last I heard there was no foundation to the story.

5. From Sydney Porter:

In Project Gasbuggy, what was the total exposure in man-rems? How was this exposure received? How can it be reduced in future operations?

ANSWER:

I guess I should clarify one thing, when those down-hole rams detected the leakage of gas, the radioactivity coming up through the stemming, rather, the first sign of this was seen at something like five hours, and when it indicated that the levels as measured by the down-hole rams were continuing to rise somewhat, the cables were cut and the hole was sealed off. Something less than a curie of noble gases was released. I believe it is in the neighborhood of one curie which is the reason, of course, the PHS monitors could not see it off-site. As far as the original question goes, only two individuals associated with the project received external exposures as measured by film badges. A radiological monitor received 70 mrem while one of the laboratory scientists received 105 mrem. The monitor's exposure is believed to have been incurred while working with radioactive sources during instrument calibration. The scientist's exposure was probably incurred at the Nevada Test Site while working on another project. Neither exposure is considered to be related to any release of radioactive material from the Gasbuggy detonation.

From the day of the detonation through April 1969, there have been no measurable internal exposures (as determined by urinalysis).

PUBLIC HEALTH SERVICE SAFETY PROGRAM

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ABSTRACT

Off-Site Radiological Safety Programs conducted on past Plowshare experimental projects by the Southwestern Radiological Health Laboratory for the AEC will be presented.

Emphasis will be placed on the evaluation of the potential radiation hazard to off-site residents, the development of an appropriate safety plan, pre- and post-shot surveillance activities, and the necessity for a comprehensive and continuing community relations program.

In consideration of the possible wide use of nuclear explosives in industrial applications, a new approach to off-site radiological safety will be discussed.

* *

The Public Health Service Safety Program began in 1954, when the U. S. Atomic Energy Commission (AEC) and the Public Health Service (PHS) entered into a contractual arrangement called a "Memorandum of Understanding."

This document stipulates that the PHS is responsible for assuring the safety of the public - off the test site proper - from any nuclear tests conducted by the AEC. Although the original document referred to the Nevada Test Site, just north of Las Vegas, we have since participated in tests conducted in New Mexico, Mississippi, Alaska, Central and Northern Nevada, and the Pacific.

There were four oriiginal objectives of the PHS program:

1. To verify the off-site radiological situation associated with tests to insure protection of the public from radiological and other effects of nuclear testing; and, in the event unacceptable situations develop, to effectuate appropriate protective actions as required.

2. To document, through radiation monitoring and environmental surveillance, the radiation exposure to off-site areas.

3. To assure the public, through personal contact and a program of community relations and public education, that all reasonable safeguards are being employed to protect public health and property from the effects of testing.

4. To investigate incidents involving radiation or its effects which could result in claims against the U. S. Government or create unwarranted adverse public opinion.

In recent years these objectives have been supplemented with three additional objectives:

a) To document any increase in environmental levels of radioactivity due to nuclear testing.

b) To conduct special studies to determine transport phenomenology of radioiodine in environmental and biological systems and to determine its effect on man.

c) To assist other agencies in the protection of the public from injury due to the seismic effects of nuclear tests.

The surveillance program was initially limited to the area within approximately 300 miles of the Nevada Test Site. Subsequently, the program objectives were expanded to include the 22 contiguous states west of the Mississippi River, and to the other areas when tests are held outside this region.

Keeping the aforementioned objectives in mind, the PHS program can be subdivided into six general categories:

1. Monitoring and surveillance programs.
2. Population and milk cow statistics and distribution.
3. Community relations and public education.
4. Veterinary investigation.
5. Medical investigation.
6. Bioenvironmental research.

At this point I would like to briefly review with you the essence of these six categories and then take you through an actual Plowshare project, Gasbuggy, to illustrate how the program and objectives are carried out.

Monitoring and surveillance includes routine surveillance of air, water, milk, and vegetation, and event-oriented surveillance performed by mobile teams in conjunction with specific events. Detailed population and milk cow surveys are conducted around sites prior to tests. This census is detailed as to numbers of adults and ages of children by specific location. The survey includes all individual family cows as well as grade grade A dairy cows.

The results of monitoring and surveillance efforts just mentioned are continuously scrutinized to determine the possibility that there was or will be significant ingestion or inhalation of radioactivity.

The Southwestern Radiological Health Laboratory (SWRHL) operates a sophisticated and extremely sensitive whole-body counting facility as a part of our Medical Program. The mobile monitors and aircraft crews are more directly exposed to any effluent cloud than the general population. As soon as possible, these men are returned to the laboratory, appropriate bio-assays are made, and each man is given a whole-body scan to determine the amount and distribution of radionuclides in the body. These data, together with dose estimates derived from radioactivity in milk and water samples, furnish conservative estimates as to the maximum doses that could have been received by the general population.

Continuous efforts are made to retain good relations with the public through personal contact, the dissemination of timely information on nuclear events, and an explanation of the steps being taken to assure public safety. An important part of this program is the day-to-day contact of SWRHL monitors with the people in the performance of their duties.

To the general public, nuclear explosions instantly recall the horrors of Hiroshima. This association and the resulting fears must be treated with respect by the field monitors, who at the same time explain technical details of the particular event being conducted and the associated safety measures that have been or are being taken. In many cases the public actively participates in the safety program by operating air, milk, and water sampling stations as well as exposure rate recorders.

The safety program is not only concerned with radiation effects on man, but the animal population as well. The veterinary or animal investigations program was originally established during the atmospheric testing days to investigate claims of beta burns to domestic livestock and wildlife. Although since the advent of the limited test ban treaty, the number of such claims has diminished considerably, we still, from time-to-time, receive complaints from ranchers with sick animals. Each of these claims is carefully and thoroughly investigated and the disease or ailment is diagnosed. The veterinarians assigned to this program work closely with local veterinarians and participate actively in professional veterinary organizations. In addition to these activities, an experimental beef herd, in excess of 40 animals, has been maintained on the Nevada Test Site, from which samples of bovine tissue and bone are taken periodically to determine the concentrations of fission and activation products. A comprehensive study of wildlife on and adjacent to the test site has, and is, being conducted in cooperation with other agencies to assess the radionuclide content of edible species. The results of these studies are available in the open literature and show no radiation either to the animal or the consuming public.

Physicians on the laboratory staff, trained in radiation medicine, investigate claims of personal injury from the public. They also operate what is called the Medical Liaison Officer Network, also referred to as MLON. This network is comprised of physicians in almost all of the 50 states who are knowledgeable in radiation injury. Local investigations in the area immediately surrounding the NTS are made by the Laboratory's physicians, whereas those at greater distances are handled through the MLON physicians. Whichever method is used, local specialists may be called into the investigation for consulation or assistance; for example, in an investigation involving a skin condition, a dermatologist may be consulted.

The philosophy of the MLON is not to state simply that this is or is not a radiation injury, but rather to make a definitive diagnosis.

Simultaneously with the above mentioned action programs, the Laboratory conducts long-range safety studies as part of the Bioenvironmental Research Program. As an oversimplification, this program's mission is to investigate the transport and biological effect of radionuclides as they move from the source to man through the food chain. Initially, the program was established to investigate the behavior of radioiodine, although other radionuclides of concern are or will be investigated. Again, stated quite simply, the objective of this research is to develop reliable predictive models, whereby having a known source term and known meteorological conditions, you can predict to an accuracy of a factor of two at the 90% confidence level the amount of radioactivity in the food chain available to man within a fallout area. It is anticipated that our investigations into radioiodine will permit us, by mid-1969, to predict the average peak levels of radioiodine in the milk of dairy cows fed feed from a fallout area - when the source of radioiodine and the meteorological conditions are known.

Other speakers have referred to "Project Gasbuggy." I too would like to use it as a typical Plowshare underground engineering experiment and illustrate how the above-mentioned safety program operates.

As has been mentioned, Gasbuggy was detonated on December 10, 1967, in a gas-bearing media approximately 55 air miles east of Farmington, New Mexico. The actual concept of the experiment was developed some years before, and in 1965 the Laboratory was first approached to do a paper study of the environment. This feasibility study, with participants from many AEC contractors and the Lawrence Radiation Laboratory, resulted in the conclusion that the project could indeed be carried out with safety and a promise of success in fulfilling the technical objectives. When the agreement was signed on January 31, 1967, between the Government and industry, the full program effort began.

At this point, our Laboratory made the initial contact with officials of the State Health Department of New Mexico. We outlined the project as proposed by the AEC and asked the State's assistance in conducting the Off-Site Radiological Safety Program. Working in complete partnership, the staffs of the Laboratory and the State commenced the initial gathering of census data on population, domestic livestock, wildlife, and other environmental media necessary to develop a comprehensive program. After receiving source term information and possible meteorological conditions, these data together with the census data were consolidated and analyzed, and a draft operational safety plan was developed. This plan, which pointed out certain limiting conditions, i.e., evacuation areas or the need for post-shot protective action procedures, was forwarded to the AEC for review.

The AEC safety review considered all factors affecting the safety of the project; among these were the depth of the device, the proximity of an aquifer to the detonation, and the location of gas production wells with respect to ground zero. The device was considered to be overburied by safety standards at the Nevada Test Site since it was emplaced at a depth of 4,240 feet. A device of the same yield would be considered safely emplaced at a depth of approximately 1,200 feet. The nearest aquifer was considered to represent no problem since the lowest water-bearing formation was approximately 560 feet above the shot point. The site chosen for the project is on land leased by the industrial participant, El Paso Natural Gas Company; the only wells in the area belong to them, and the closest production well was 3,400 feet from ground zero. As an added precaution, all producing wells within a five-mile radius of ground zero were physically separated from the gas transmission system. Nevertheless, the AEC hypothesized all possible failure modes which could release radioactivity into the atmosphere, the ground water, or into the natural gas production system. Although these failure modes were considered highly unlikely, the AEC authorized the Laboratory's comprehensive radiological safety program for Project Gasbuggy.

In accordance with the operations plan, the SWRHL pre-shot preparations were begun in June 1967. During the summer of 1967, the census was completed out to a distance of 100 miles of the shot point. In addition, all mining and tunneling operations within 50 miles were located. As the census information was collected, SWRHL personnel distributed printed information to the public explaining the nature of the experiment and answered questions by the local population regarding their activities. The community relations program was intensified during later periods when the SWRHL Project Officer and the State Health Department officials visited local officials in the surrounding communities. The initial environmental sampling was begun in August 1967. This included the collection of daily air samples at 35 locations around the site; the collection of milk from 22 stations - 13 representing family milk cows and nine grade A dairies; 34 water sampling stations were established, 6 representing municipal water systems, the others open or well water sources.

A new dimension was added to the environmental sampling program for Project Gasbuggy in that 15 samples of natural gas from producing wells in the area were sampled and analyzed pre-shot. Natural gas produced in the San Juan Basin was known to contain measurable quantities of Radon-222. Some had hypothesized that the ground shock and resulting ground motion from the explosion would shake the medium to such an extent that the amount of Radon found would markedly increase in the natural gas. Incidentally, this did not happen.

A network of thermoluminescent dosimeters (TLDs) and film badges was established at 50 stations surrounding the test site in October of 1967. The TLDs are, in our opinion, reliable personnel monitoring devices with a low sensitivity of 4 mR.

Medical and veterinarian activities began during the summer of 1967 when the respective officers made visits to various state and local physicians and veterinarians and briefed them on the safety programs as well as the medical aspects.

Approximately 30 people from SWRHL and the State Health Departments of New Mexico and Colorado were assigned to the program and were on station on December 1, 1967. A short training course was given for State personnel on procedures to be used and all personnel were oriented with the area around the site. At shot time of December 10, 33 personnel were on station, including monitoring teams in two aircraft orbiting the site.

As you all know, the experiment was fully contained. Had there been any prompt venting or seepage from the project, we would have been fully prepared. An on-site remote area monitoring system would have telemetered information back to the AEC control point, and the aircraft teams would have measured and tracked any airborne radioactivity. This information would have been instantly available to the PHS Project Officer who was in constant communication with the mobile ground monitoring forces. These teams would have been deployed into the path of any cloud to assess actual radioactivity levels at downwind distances. Should the situation so warrant, the populace could either be asked to remain indoors during the cloud passage or to evacuate in accordance with a prearranged plan.

In addition to this emergency type action, our protective action plan incorporates provisions to reduce radioactivity levels in the food chain. These may involve the covering of forage used by milk cows, substituting "clean" forage, or as a last resort diverting milk supplies to cheese or other dairy products to allow for radioactive decay.

Since there was no venting, the environmental sampling program was greatly reduced shortly after the experiment; otherwise, these programs would have been continued until background levels were reached. (A reduced safety program has been continued at the Gasbuggy site in connection with the flaring operations of the experimental well.)

It is our conclusion that from the safety standpoint the project was a success. The population was not exposed to any airborne radioactivity from the event; no evidence has been found of any contamination to the ground or surface waters; and there has been no migration of radionuclides into other gas-producing wells or the existing natural gas distribution system. We also believe we were well prepared so that our personnel could effectuate pre-developed emergency procedures to insure the protection of the public health had an unforeseen accident occurred.

In closing, I would like to leave you with a thought and a challenge for the future . . .

As you all know, the Atomic Energy Act of 1949 reserves exclusive jurisdiction to the AEC for all health and safety matters connected with the detonation of nuclear devices. If the use of nuclear explosives proves to be a success in the recovery of gas, oil, or minerals, it is doubtful that either the AEC or the PHS would have the manpower or other resources to handle all of the possible commercial utilization of this new tool. What then? Some discussion is presently taking place that industrial organizations could accept the safety responsibility along with the site development, drilling, etc.

What is the role of the State? PHS? AEC? What kind of safety program is adequate to protect the public when the application of this energy is moved from the experimental into applied use. Who decides when this transition takes place? How many experiments are necessary to conclude the program is no longer experimental? How many experiments are necessary before existing comprehensive safety programs can be reduced in scope? Does this new resource enter into the same category as an oil refinery, a chemical plant, or a nuclear power plant? There are, of course, other questions relating to public health, dealing with appropriate standards as to the consumer product. These will be covered in other papers. Nevertheless, public health agencies must think of the future now for, if industry is to seek the benefit in the peaceful application of nuclear explosives, the time to consider the inevitable changes is fast approaching. The questions I have raised and to be frank I do not have the answers are mostly jurisdictional in nature. We can not afford, however, to become involved in such jurisdictional disputes, when the need for adequate protection of the public's health is at stake.

QUESTIONS FOR JOHN R. McBRIDE

1. From Robert Karsh:

   Do you monitor children who are known to be strategic bio-concentrators of iodine-131, or do you merely extrapolate from measurements on cows, milk, and adult employees?

   ANSWER:

   Although this didn't happen with a Plowshare experiment, we do have accidents that occur and we make all the effort that we can to prevent them. One of the weapons shots did vent and activity was sent north over the Test Site and a community called Hiko. There were about 80 people living in the town and we monitored every one of them including the children. And for some reason if you extrapolate from milk to people, you will find that their dosage should have been about five times higher than they actually were. I think part of this is because the FRC standards assume that a child drinks a liter of milk and I don't think this is so. We do monitor, we do look at the children very closely and we are concerned with them.

2. From Robert Karsh:

   What warning system is used or contemplated when iodine-131 is found to be too high in the milkshed?

   ANSWER:

   We have a source term - this is given to us before the shot occurs - so we can calculate from the amount that under certain meteorological conditions that should exist at distance. This is worked out before the shot even goes. Now if, and by the way I serve and Dr. Carter serve as members of the AEC Safety Panel before each shot, and if it appears that this is in excess of the FRC guides, the shot is postponed until favorable conditions develop. Now even with all this care is taken, if the meteorology changes and it does, we take immediate action. In a case say in the collection of milk from family cows, when we sample the milk, we take all the milk available. Therefore, the family is not the receptor. In other cases, we are prepared to bring clean feed in for the cows. We are also prepared to substitute milk and of course notify the appropriate state and local officials of this action in advance.

3. From F. Chin:

   Could you comment on the extent of the PHS role in assistance for off-site seismic effects which you briefly mentioned as a supplemental activity?

ANSWER:

Since we have so many people in the off-site area and we have contact with miners and ranchers and the populous in general, we more or less do this as an additional duty. We take the ground motion experts' predictions, and then warn the populous of the shot advising for instance to stay out of a mine during this period, asking to stay off of scaffolding and precarious perches and high places. Basically, we have been used to carry the message.

STATE AND LOCAL SAFETY PROGRAM

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ABSTRACT

This paper will give emphasis to the need for an increasing role of the states, along with the Federal agencies, in the Plowshare Program in order to assure state and local confidence with respect to the safety of their residents as the Federal government seeks new methods to benefit society.

First will be stressed the age-old principle of control at the source.

Other factors to be discussed are monitoring; standards and their use; control action; public relations; predictions and the need to have certain advance knowledge of tests - even if security clearance is necessary for appropriate state representatives; the state and local government responsibility to their citizens; the isolation of national decision making from state and local concern and responsibility; cost assessments and their responsibility; and research as it relates to the ecological system as well as the direct short- or long-term effects of radioactivity on man.

The threat to human health of radioactivity in the environment has received growing attention in the post-war period, and has caused health officials in the United States considerable concern. The almost unlimited possibilities for useful application of radioactivity or operations resulting in radioactivity will attract the intellectual and practical efforts of mankind for centuries to come. How well these applications are thought through in advance will determine whether this new tool will be a blessing or a curse to society.

Much evidence has been accumulated to date to show the feasibility of controlling radioactivity at levels which will not result in unacceptable hazards. At the same time we must not forget that radioactive fallout in the 1950's from weapons testing was of such a degree and composition of long-term half-life nuclides that it may be many years before we actually are certain about any resulting hazard. Thus, past experience and the vast complications of the subject argue against any complacency about our present level of knowledge. We simply cannot take it for granted at this juncture that our past control of radioactive exposure has been adequate nor that it will continue to be adequate without greatly increased attention to the entire subject and greater planning effort directed toward major decisions concerning use of the new tools we have found. This symposium is in itself an indication of this concern and a response for that concern.

Control of environmental pollution at the source has been regarded as the most effective means of removing or forestalling threats to the health of the population. The philosophy is still sound, and must be applied in all cases to the limit of practicality, and especially in the case of radioactivity, since everyone agrees that no unnecessary radioactivity should be imposed on the environment. When the standard practice of treating effluents becomes impractical, as seems evident in the Plowshare Program, the decision as to whether or not to continue promoting the possible benefits of a program to society revolves around questions of how adequate are our predictions and measurements of contamination and what are some long-term effects of pursuing a certain course of action. The subjects thus opened up include monitoring, standards, controls, public relations, methods of prediction, state and local government responsibility, the isolation of national decision making from state and local government concern and responsibility, costs of surveillance and related actions, and planning of research.

Utah's geographical position with respect to the Nevada Test Site has served to emphasize the critical responsibility devolving on state and local health officials in protection of the population against radioactive contamination, especially when source control is not feasible. Several papers earlier in this symposium have identified our downwind location. Other states have been involved in the usual sources of radioactivity, but many of these do not present the problems of extensive monitoring or the critical public relations problems which have been experienced in connection with tests in Nevada.

As a result of the 1962 contamination experience, which involved Utah milk supplies to a high degree, Utah was obliged to move into an extensive monitoring and laboratory program which it could not have supported without substantial financial help from the Public Health Service. The 1962 event has been reported before and will not be elaborated here except to say that it has sensitized people in Utah to the potential hazard which exists at the Nevada Test Site.

As indicated by SLIDE 1, at the present time Utah has eighteen air monitoring stations which operate twenty-four hours a day throughout the year. Operators are instructed to call the State Health Division personnel involved, night or day, when readings of atmospheric radioactivity exceed a certain pre-determined figure. This is calculated to give early warning for the purpose of intensifying the regular milk monitoring procedures. Bi-weekly samples from milk tankers (routes shown on the slide) covering all major grazing areas in the state are analyzed for iodine-131, strontium-89 and -90, cesium-137, and barium-lanthanum-40. The existence of this monitoring network in 1962 would have better prepared Utah for that event. The Utah network has gradually evolved since that time.

SLIDE II indicates air monitoring results collected in Salt Lake City, and shows examples of types of results obtained with this monitoring network. The first peak resulted from the cratering shot of 1962; the second, in the same year, is from an unscheduled venting at the test site; the next three peaks are those resulting from Chinese testing; and the final one is from the scheduled venting at the Nevada Test Site in December 1968.

In the middle and late 1950's the Salt Lake air monitoring station, the only station in continuous operation, identified atmospheric fallout from the Nevada Test Site at levels 5 to 7 fold greater than the 1962 Salt Lake City peak shown in Slide I.

The pattern of deposition of fallout over the state from this "Schooner" shot is indicated by SLIDE III which shows the air results of each of the Utah stations. Charts for each of the Chinese shots show a similar pattern for both air and milk.

In addition, a statewide monitoring system for detection of tritium in water is now getting underway. These activities, related almost entirely to earlier testing programs, will become more important as the testing activities increase, whether due to weapons testing or Plowshare projects.

Not only is the Utah monitoring system presently considered to be an absolute minimum commensurate with the possible hazards involved, but it is furthermore our opinion that the system must be expanded in the future if the proposed Plowshare Program continues. One of the reasons for this is the past history of prediction failures which were related initially to weapons testing programs. There is ample evidence in Utah to show that the most careful meteorological predictions of fallout paths do not materialize in every case, and that without an extensive monitoring system there is no way of detecting the possible exposure of the population resulting from certain atmospheric testing activities. And, for that matter, there is no way to assure the population that fallout did not occur.

Needless to say, the State or local health official is not discharging his responsibilities in any adequate degree if he is not prepared to answer with reasonable precision the questions "Was there any environmental contamination in Utah as a result of the last test, where did it occur and at what levels?"

Constant updating of laboratory capability is also a necessity, resulting in added expenses far beyond those originally contemplated. For example, at considerable extra cost, we have recently acquired a liquid scintillation counter to handle our tritium samples. We are now faced with the acquisition of an additional chemist because our original staff is far overloaded in view of the increasing amount of envirionmental monitoring found necessary. This will be intensified, of course, as activities involving nuclear fission increase in the area.

Assuming that monitoring capabilities are adequate, the question of standards is the next important consideration. Much work has been done in this area both nationally and internationally, and ther exists an abundance of highly technical reports related to the subject. What is sometimes lacking is interpretation in a way which will make application of the standards practical as well as sound in the sense of protecting public health. This problem is being attacked from many angles and hopefully will yield to an adequate solution; however, it must be recognized that new scientific information is being accumulated at such a rapid rate that we will never have a set of standards which are not subject to revision as new evidence comes in.

Differences of opinion with regard to standards are inevitable. This has been so throughout the history of environmental controls, and radioactivity could not be expected to constitute an exception. State and local health departments must rely heavily on the resources of the Federal Government and others in developing standards, but in the final analysis they must assume full responsibility for the precise levels of protection which are applicable to a given segment of local populations. Therefore, they cannot blindly accept standards which are handed down from some other agency, but must evaluate them thoroughly with whatever resources they can develop. One such resource in Utah is the Radiological Health Advisory Committee. This committee was appointed in Utah after the 1962 incident, and is composed of well-known and highly respected experts in their fields. The committee's recommendations are respected and provide the Health Division with a factual and effective base for action. The committee acts as a clearing house for technical radiological health information and is responsible for recommendations to the State Board of Health on various points, including standards, operating surveillance and control programs.

A foreseeable complication in the area of standards development is in the increasing number of ways by which human beings can be exposed to radioactivity. This grows out of the great usefulness of radioactivity both to science and industry, as previously mentioned, and the guarantee that under these circumstances inventive minds will be devising new applications continuously. Standards are often based on exposure from a single source, and shielding and other requirements are based on the single-source, multiple-exposure concept. Not only are some states potentially exposed to nuclear testing as an important source of irradiation, but they must be continually concerned with multiple exposures in numerous radioactive devices which may come to be in almost constant use. This seems to suggest a need for rather comprehensive planning in the standards-setting process.

The question of control action more often than not relates to controls over a rather specific use of radioactivity, as radiography, isotope use, laboratory experimental use, etc. In general, it can be said that good progress has been made in this area and controls so far adopted are achieving some success. In Utah, the word "control" conjures up a necessity of taking action with respect to use of foodstuffs, and possibly water, resulting from incidents which occur beyond the State's limits of jurisdiction, such as at the Nevada Test Site. In 1962, Utah found it necessary to actually apply certain controls to the use of milk, but the problems related to that experience make us sensitive to the need for continual refinement of plans which will be brought into effect in the event of another major contamination incident.

It must be recognized that if our monitoring capabilities are adequate and if the information achieved through monitoring is properly assembled and evaluated, the term "control" might possibly be extended to some efforts at curtailment of Plowshare types of testing. This question was never seriously considered in connection with weapons testing, which have a strong defense connotation. It is obvious that it must be considered in all cases of peaceful application of nuclear energy.

While this paper does not presume to determine the need for nuclear testing, weapons or Plowshare, nor to determine the validity of its purpose, it does presume that once this determination is made to fulfill government policy, all effort must be devoted by the Federal government to protect the health of the public.

Apart from the real dangers to the human population which radioactivity causes, there is another question embodied in the term "public relations" which has great significance, not only in Utah but everywhere else in the country, and possibly in the world. Radioactivity is a glamour subject, and has attracted wide attention, even on the part of the average citizen. Sometimes, besides being fascinating, it is as someone said, a little "scary", and this gives rise to problems which state health departments must face.

A good and effective public relations program in this area is absolutely essential under any circumstances, but it must have equal priority with control action in the case of radioactivity, and particularly the type of radioactivity which originates beyond the State's borders as a result of planned action by man.

The State and local agencies must be prepared to reassure the public that no hazard exists just as often as they must be prepared to take control action. Sometimes the most innocuous release in the press about the existence of radioactivity in any concentration will evoke a strong public reaction which needs to have a counter reaction by responsible officials. At no time should the public be fooled about the true facts, but obviously, when no hazard exists, the State agency should be in a position to state this fact unequivocably and with solid backing from scientific measurements. This is one of the major reasons for the extensive monitoring and laboratory capabilities already mentioned.

This problem also requires some expertise in dealing with the press, which again devolves on the State and local officials. Even the best scientific information can be quoted incorrectly and produce a near public panic as the result of misinterpretation. Obviously, much energy should be directed toward the prevention of such misinterpretation.

One aid in connection with these problems could come from detailed knowledge which might be available with regard to planned tests. In the past certain tests of necessity were shrouded in secrecy, and release of advance information even to State officials was possible only to a very limited degree. As testing becomes more complicated, it becomes more and more necessary that State officials have complete details of planned tests prior to the event, in order that monitoring and other activities can be geared to meet the needs. If release of such information to these officials requires security clearance, this should be provided automatically, after the necessary checks, of course, to insure adequate security. It seems likely that no one can provide all of the complicated monitoring needed if there is no hint as to the specific isotopes which are likely to be produced. Again, as important as this knowledge is to those conducting the tests, it is equally important to State and local officials who have the responsibility of protecting the citizenry within their jurisdiction, and of avoiding misinterpretations of information which could lead to panic or other undesirable results.

An aspect of the overall problem which needs more emphasis is the isolation of national decision-making from state and local concern and responsibility. It seems unlikely that a Federal Agency making a decision whether or not to conduct a test program can have the same sense of responsibility to a specific population group as a state or local health officer who has to cope with the results of that decision. At the State level, the health agency has almost daily contact with many of the people who may be involved in any adverse developments, he has almost daily contact with industry officials who might be involved, such as the dairy industry, and he is going to be held more directly accountable for any adverse effects of the decision-making process. Involved here, of course, is the public relations problem previously mentioned, but it is not a matter alone of public relations.

The day-to-day decisions of the State health officer are put to test in a practical sense and reacted to more promptly and directly than can ever be the case for a similar official at Federal level. Even if the State official desires to hide behind the curtain of Federal standards and responsilibity, he cannot long exist in this position. Sooner or later, he will have to face up to his responsibilities or turn his task over to someone who will. The point is that the State health officer or his authorized representative must be directly informed of all pertinent data of any testing program which may distribute radioactivity over the State area.

This, of course, raises the question of who shall bear the costs of added surveillance and control procedures. Some basic monitoring costs are the proper responsibility of state programs, but it seems logical that the Plowshare program, being essentially of a research and development nature, should absorb most of the cost imposed on States for radiation monitoring related to this program, and also of the associated control.

As has been mentioned previously, the cost of monitoring can become a major item for a state, and could be completely beyond state capabilities. This will vary with each state. Currently, however, few states, if any, are adequately prepared. Nevertheless, if the hazard is imposed by decisions to aid society through development of new processes, those responsible for the decision should see to it that states have enough resources to provide the basic essential monitoring, and to expand it as necessary to meet new needs, whether these develop from expanded uses of radioactivity or from advances in knowledge which dictate greater sophistication in monitoring and analysis capabilities. This need will continue to vary with the States. It is most critical for Utah because the State is both relatively small and its location is readily subject to effects from the testing programs.

Other costs, which hopefully can be avoided, but which still must be considered as possibilities, relate to control action found necessary when food or water become contaminated beyond acceptable use levels. Utah's 1962 incident was estimated to result in total cost to industry of about $80,000 and total cost to government, beyond normal activities, of about $37,000. Compared to the high cost of testing such an explosive, these costs are small, but for states of small population these are large, and much more so when repeated and when added to other related costs such as monitoring and laboratory services. Deliberate planning to experiment with peacetime uses of atomic energy certainly should include a positive plan to pay such costs, however large they may become. Acceptance of this philosophy might succeed in transferring some of the direct responsibility mentioned previously from local to national level.

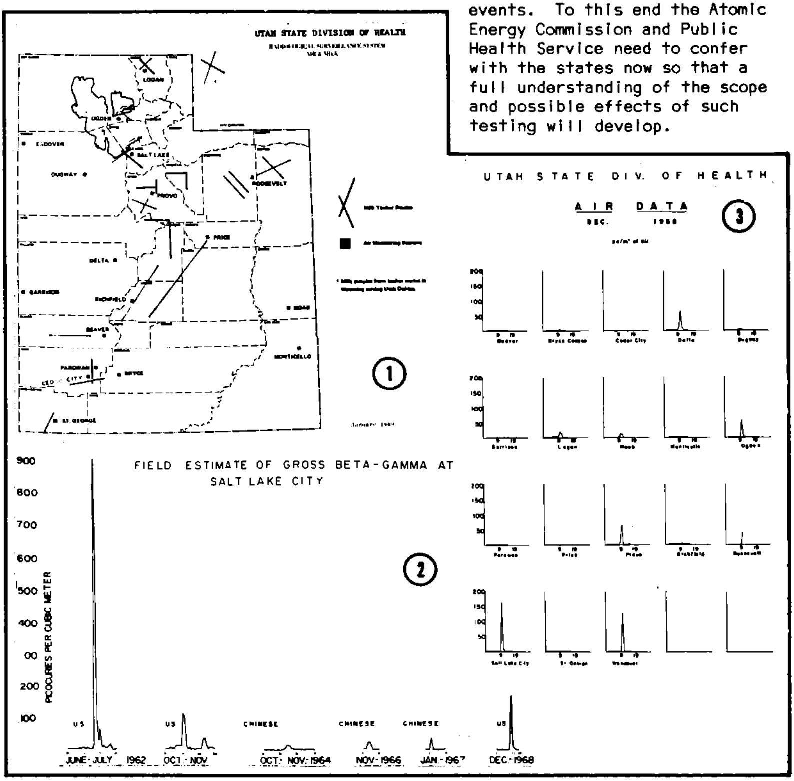
Another cost considered to be an essential part of the activities under discussion, although not exclusively attributable to them, is that of research. Not only is basic research involved, but also some applied research as it relates to the eco-system and the long-term results of small deposits of radioactivity in the environment. These small deposits cannot be considered immediate hazards under any circumstances, and yet they might eventually be serious hazards, particularly when they involve isotopes with long half-lives.

A research program to investigate all aspects of this problem cannot be simple and certainly will be costly. Most of this research is already being done, but again, Utah's peculiar relationship to the testing area seems to argue for an even more complete effort in this particular area, as well as projected research activities for a long time in the future. While we are emphasizing Plowshare activities at this Symposium, it is not too late to also emphasize the need for support of research activities already underway or that should have been undertaken as a part of the weapons testing program. If this is not accepted in advance, it may prove difficult to accomplish afterwards. For example, the Utah-Nevada-Arizona fallout study was initiated after the event of 1962. This year we are finding great difficulty in continued financing for a series of reasons none of which we in Utah are able to accept. Such research should not exclude the development of better methods of monitoring as well as development of control methods which might some day become necessary.

Again, as mentioned previously, the allocation of this type of cost to the Plowshare program should be done with the full realization that it may lead to decisions to curtail the testing program. Certainly this is not too much to ask in the interests of not only the population in Utah but populations through the country and possibly the world.

It should also be mentioned that there are still wide gaps in our knowledge covering the direct short-term effects of radioactivity on man. This became evident when we were pressed for decisions about how high atmospheric levels could get and for how long before we would declare a crisis and instruct the public on special protective actions. Existing standards relating to this matter simply are inadequate to be of real practical value. At least, in Utah, I believe we would take control action at lower levels of exposure than the current standards seem to suggest. While it may be true that some of the research in this area needs to be financed by other agencies, it again seems logical that the Plowshare program needs to be given rather direct responsibilities of this nature.

While this paper has given emphasis to radiation hazards by fallout, this is because of our past experience. We must now also be concerned with seismic events. To this end the Atomic Energy Commission and Public Health Service need to confer with the states now so that a full understanding of the scope and possible effects of such testing will develop.



QUESTIONS FOR G. D. CARLYLE THOMPSON

1. From Hal Mueller:

   Was any Iodine-131 detected in cow's milk by your network as a result of the December 1968 detonation? If yes, how much and where?

   ANSWER:

   No

2. From Mr. Phelps:

   Earlier in the symposium, it was stated that the Director, State Health Department, Utah was informed about the cloud trajectory and radionuclide composition with regard to Plowshare cratering events. Do you inform other groups (i.e., the University of Utah Radioecology Program) of the possibility of fallout and its probable deposition pattern?

   ANSWER:

   This has been a changing matter because in the beginning the information we received was restricted to our own official use. This was not shared. Later on as we got information that could be shared, we did so. Because again the classification of this information we got was not fully understood. I think the differences that have arisen have resulted in clarification. I understand now that the information that we are going to recieve, we will be able to share. I can't say that is going to be the case though, because I haven't received the information yet in regard to some of the future tests. I think there have been some places for misunderstanding in Utah on this very point.

3. From Walt Kozlowski:

   You mentioned "unacceptable hazards," would you describe some hazards which would be "acceptable?"

   ANSWER:

   Well, I think this gets back to the discretion of the designer to learn how much radiation imposed on the population is really necessary. This is the old discussion of what is necessary. From our standpoint, we don't believe that radiation coming to Utah is an area over which we have direct control. If it is determined to be necessary by national policy then we need to have the information available to monitor and to take corrective action should it arise. I presume that if the predictions that we are going to get were indicative of high level fallout, we would protest it. I have a committee, though, which I'm sure would meet to discuss this point. The committee already has adopted a policy about which I testified before the Joint Committee on Atomic Energy and responded to the fact that we didn't like the new standards and therefore we would use our own judgment in these standards. So I don't believe I can answer that question anymore precisely than to deal with it in the nature of the event, should it occur, and we would probably have to look at it and make our own judgment.

4. From Walt Kozlowski:

Who are some of the well know experts on the radiological health advisory committee?

ANSWER:

We have two practicing radiologists, we've had a recent change because of illness, but at all times these men have been highly respected in their field in the state of Utah. We have had some health physicists. We've had some men from industry. We have the leading physicists from our three large universities. We have nine people - I don't know if I have covered them all or not.

5. From Dr. Pelletier:

How many air sampling stations do you think it is necessary to have in Utah to assure your people that they were not exposed to the cloud of a given event?

ANSWER:

This is a question the legislature asks me every time I go for money. As long as we don't have any event, they think we don't need the stations. We didn't have any trouble this year after the December event. Actually, the stations which we operate are partly owned by us and partly owned by the Public Health Service which we operate, and some of them, of course, are using different types of instrumentation for which we are getting comparative results. But I would think we would need about what we now have and if we maintain this, we would be able to determine the fallout in any movement from outside the state. I don't believe every state would need the coverage we have as they move farther away from the Test Site.

6. From Robert Karsh:

The Dugway CBW incident last year made it apparent that the state of Utah did not get advance information of what was being tested on March 13. Are you now getting this advance information in the radioactive field? Minnesota is now concerned with the possibility and legality of state rules more stringent than those of the AEC. Does Utah foresee this?

ANSWER:

Just to clarify that first part of the question, I believe we are now involved in being informed from Dugway about all of the events that occur there. Heretofore, we were only involved in the biological events, not the chemical events. We were also involved in the beryllium events at Dugway. But the setup which is now in operation is the same for chemical events as for biological events. With respect to the radiation aspect, we haven't had any event since December, but I have been assured that we will be fully informed of anything that we need and we are having some of our staff visit the Southwestern Radiological Health Laboratory for technical consultation with regard to sharpening our capability on our own instruments with respect to some of the isotopes that have been mentioned here in this conference. We do use the Southwestern Radiological Health Laboratory, of course, for reference for specimens on a number of things and we split specimens with them. I might also say, going back to the former question, that one of the reasons we are able to operate these stations as economically as we are because we locate them in connection with our air pollution program for other air pollutants and so we are able to have a separate device while the man power is common. The daily changing and checking of motors and pads and testing samples is done by the same person in multiple areas. This reduces the cost substantially to what you would have to do if you were just operating a fallout network as we were originally.

(Second part of question.) I think we have already given indication to that answer by indicating how our own rad health advisory committee reacted to the new FRC standards when they were adopted a few years ago and prepared the statement which I used to testify before the Committee. When the chairman of the Committee asked me who was going to apply the standard in Utah, he said, "Aren't you?" and I said, "Yes, we are," and he said, "Well, that's the answer to your question." So I presume we will apply the FRC standards in our own way in Utah; if that's writing a Utah standard why it will have to be a Utah standard I guess. It does pose a problem and that's what I said in my paper: that I think we have to have some full discussion of these standards. As you remember back in those days it was said that you were changing the rules of the ball game just as you are about to score a touchdown and there is some bad reaction to that in several of the states. I wouldn't be surprised if Minnesota is one.

7. From John Martin:

To what extent does your state health safety program on radioactive fallout exposure cooperate or collaborate with local universities and private industry researchers?

ANSWER:

I don't know of any private industry researchers in this area in Utah. There are some in the universities and I'm sure I can say that the communication can be improved in this respect.

SESSION IV - BASIC RADIATION PROTECTION GUIDANCE

Chairman: Dr. Gordon Dunning
Department of Operational Safety
U. S. Atomic Energy Commission
Germantown

THE PHILOSOPHY
BEHIND THE FEDERAL RADIATION COUNCIL GUIDES

Paul C. Tompkins, Executive Director
Federal Radiation Council*

ABSTRACT

The basic philosophy of the FRC in making recommendations for the control of radioactivity associated with normal peacetime operations is given in FRC report 1. Radiation Protection Guides for application to activities such as Plowshare would be derived on the basis of this philosophy. Considerations involve a balance of benefit versus risk for each Plowshare activity that is proposed for industrial application using potential exposures small in comparison to the basic guide of 0.17 rem per year as the primary reference condition.

Alternate approaches to achieving an appropriate balance have been suggested. These include allocation of a fraction of the 0.17 rem per capita per year to each relevant activity; setting a universally applicable MPC for each nuclide of interest, and the concept of the dose commitment. Data to show the benefit in terms of the national need for the resource in question (e.g., gas production) and the risk as indicated by the amount of residual radioactivity is a prerequisite to setting guidance for using Plowshare techniques in conjunction with consumer products available to the general public.

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It is a privilege for me to have the opportunity to discuss with you today the general philosophy of the FRC in the formulation of basic guidance in radiation protection for use in Federal agencies. In order to gain an appreciation of the general philosophy used by FRC, I should start with a description of how the FRC operates and the general nature of some of its principal recommendations. Formation of the FRC resulted from a government-wide review of radiation protection responsibility conducted in 1959 by the Director of the Bureau of the Budget, Chairman of the Atomic Energy Commission, and the Secretary of the Department of Health, Education, and Welfare. The decision to conduct such a review was in response

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*The views expressed are those of the author and do not necessarily represent the official views of any Federal agency.

to the public confusion and concern over fallout hazards associated with atmospheric testing of nuclear weapons, and the fact that there appeared to be no single agency within the executive branch of the Federal Government responsible for the formulation of radiation protection guidance.

The study group concluded that, under the prevailing scientific assumption that any exposure to ionizing radiation is associated with some risk of causing harmful biological effects, the derivation of basic guidelines for radiation protection involves reaching a balance between total health protection, which can be achieved only if there is no radiation, and the benefits from activities causing the exposure. This balance in turn involves health, economic, social, and ethical considerations of such a nature that the person or persons making the decisions represented by that guidance should be publicly accountable. No single agency could be found with the appropriate breadth of responsibility and jurisdiction, and it was recommended that the President be advised by a Federal Radiation Council on radiation matters directly or indirectly affecting health, including guidance for Federal agencies in the promulgation of operating radiation protection standards, and in the establishment of programs of cooperation with the States.

The President accepted this recommendation and created the FRC by Executive Order 10831, August 14, 1959. The Council was made statutory in September 1959, by an amendment to the Atomic Energy Act of 1954 - PL 86-373 (section 274h).

The Council now consists of the Secretary of Health, Education, and Welfare (designated by the President to serve as Chairman); Chairman of Atomic Energy Commission; Secretaries of Defense; Commerce; Labor; Agriculture; and Interior. The Special Assistant to the President for Science and Technology also serves as an adviser to the FRC; he has always taken a strong interest in the activities of the Council and has been quite influential in the formulation of many of the basic guidelines that have been adopted.

Administratively, the FRC is treated as an independent agency. Staff members are employees of the Council and are independent of any operating agency. For example, we prepare and submit our budget directly to the BOB and appear before the Congressional appropriation committees just as all other agencies. The heart of the FRC operation is vested in its Working Group. Members of the Working Group are senior technical representatives appointed by the various Council members to convey to the FRC staff the agency interest and views in matters being developed for consideration by the Council. When the Council is engaged in a specific project, the work is conducted by means of task groups of technical people in Government, and when appropriate, consultants from the scientific community, representatives of State agencies, industry, and labor. The law states: "The Council shall consult qualified scientists and experts in radiation matters, including the President of the National Academy of Sciences, the Chairman of the National Council on Radiation Protection and Measurement, and qualified experts in the field of biology and medicine and in the field of health physics." We accordingly have a contract with the Academy to support an advisory committee to the FRC, and a contract with the NCRP to review in depth the biological and physiological models used by the FRC in developing its guidance for strontium-89, strontium-90, and cesium-137.

A sincere effort is made to get unanimous agreement on recommendations going to the President, because upon approval by the President and publication in the Federal Register, these recommendations become official guidance for Federal agencies. If there is a controversy (and this happens quite often), the basic issues are isolated with the assistance of the WG and various alternatives are considered. Attempts are then made to resolve the differences by appropriate meetings of officials directly below the Secretary level to reduce to a minimum the unresolved issues that must be solved by the principals themselves. The basic philosophy of the FRC is given in FRC report 1 and is similar to that of the NCRP and also that of the International Commission on Radiological Protection (ICRP). All three organizations have made it clear that their guidance deals quite differently with two distinct conditions of exposure: (1) in which the occurrence of the exposure is foreseen and can be limited in amount by control of the source, and by the development of proper operating procedures; (2) in which the particular exposure is accidental (i.e., has not been planned) and which can be limited in amount only, if at all, by remedial actions.

In 1962, the FRC explained the distinction between these two types of exposure conditions when it took the position that its Radiation Protection Guides (RPG) in FRC report 2 should not be used to determine when remedial action to reduce or limit the intake of iodine-131 from atmospheric testing of nuclear weapons should be initiated. It pointed out to the JCAE that the RPG's were originally developed for application as guidelines for the protection of radiation workers and the general public against exposures that might result during normal peacetime operations in connection with the industrial use of ionizing radiation. The term normal peacetime operation referred specifically to the peaceful applications of nuclear technology where the primary control is placed on the design or use of the source. Since the numerical values and the guides were designed for the regulation of a continuing industry, they were necessarily set so low that the upper limit of Range II, as shown in FRC report 2, is considered to fall well within the levels of exposure acceptable for a lifetime. Furthermore, to provide the maximum margin of safety, the upper limits of Range II were related to the lowest possible level at which it was believed that nuclear industrial technology could be developed.

These guides for normal peacetime operations are not intended to be a dividing line between safety and danger in actual radiation situations; nor are they intended to set a line at which protective action should be taken, or indicate what kind of action should be taken. There is, of course, an essential difference between environmental radioactivity resulting from a long term permanent industrial operation and that related to intermittent production from individual weapons tests or series of weapons tests. With the former, it is predictable that introduction of radioisotopes into the environment will persist at a known rate throughout the life of the source. On the other hand, weapons tests are sporadic in nature and the radioactivity produced will rise at the time of testing and decline at various rates for different isotopes after conclusion of a test or series of tests. As applied to an intermittent source, such as fallout from weapons testing, average annual intakes of radionuclides equivalent to the RPG's for normal peacetime operations should be used as an indication of when a need for detailed evaluation of possible exposure hazards and a need to consider if any protective action should be taken under all the relevant circumstances, including the probable continuity or repetitiveness of the activities leading to the release of the radionuclides to the environment.

There is substantial agreement between the ICRP and the FRC philosophies in guidance applicable to industrial practices, fallout from atmospheric testing of nuclear weapons, and accidental release of radionuclides to the environment. However, there is a substantive difference in the two philosophies regarding the applicability of the numerical values for RPG's. In its report 9, the ICRP said: "Accordingly, any dose limitations recommended by the Commission refer only to exposure resulting from technical practices that add to natural background radiation. The dose limitations are therefore intended to include such exposures as those that result from mining, from flight at high altitudes, or from the presence of radioactive materials such as radium, uranium, or thorium in concentrated form."

The FRC philosophy as applied to such technological practices as mining and high altitude flying is encompassed in two recommendations in FRC report 1. The applicable paragraphs read: "There can be no single permissible or acceptable level of exposure without regard to the reason for permitting the exposure. It should be general practice to reduce exposure to radiation, and positive efforts should be carried out to fulfill the sense of these recommendations. It is basic that exposure to radiation should result from a real determination of its necessity.

"There can be different Radiation Protection Guides with different numerical values, depending on the circumstances. The Guides herein recommended are appropriate for normal peacetime operations." As we have interpreted the Radiation Protection Guides in report 1, mandatory extension of the numerical values in that report is not necessarily appropriate and each activity of this type may be considered separately and on its own merits under the FRC philosophy. As a matter of fact, on the basis of competent scientific advice, the FRC has already set aside mandatory application of the RPG approach in deriving its recommendations for radiation protection associated with underground uranium mining. The guidance in this case is derived from an evaluation of the epidemiological information derived from the DHEW study of lung cancer rates in uranium miners as related to exposure expressed in a unit called the Working Level Month.

In common with the practices of the NCRP and ICRP, we accept the concept that there is no threshold in the relationship between exposure to ionizing radiation and the possibility of causing adverse biological effects. We also accept the concept that this relationship is monotonic; that is, the probability of causing a harmful biological effect increases with the radiation exposure. As do most professional bodies concerned with deriving appropriate practices involving radiation protection, we utilize many of the principles derived from the assumption that the relationship between radiation exposure and the probability of causing harmful biological effects varies linearly with the radiation dose, although we recognize that such a cause-effect relationship is not true in the real world. Acceptance of the linear hypothesis provides a basis for deriving an appropriate course of radiation protection, but it by no means implies that the FRC accepts this relationship as a fundamental law of nature.

The concept that guidance for radiation protection involves reaching a balance between the benefits derived from the activities causing radiation exposure and the risk resulting from radiation exposure has led to the development of several different ways of examining both the benefits and the risks. Acceptance of the linear hypothesis as a basis for the development of radiation protection guidelines and practices permits the conclusion that the total risk increases with the total man rems regardless of how these man rems may be distributed among various individuals in the population at risk. However, when there is a choice we usually consider that a very small change in incremental exposure per individual, even though it may affect a larger population, is preferable to a course of action that would limit the population at risk at the cost of a sharply increased radiation dose per individual.

A significant concept that has grown in the FRC is that reduction in risk is correspondingly achieved by a reduction in total man rems and cannot be achieved by simply spreading the same exposure over a larger number of people. This concept has been influential in the distinctions drawn by the FRC in developing its Protective Action Guides (PAG) for coping with uncontrollable exposures. An extension is the view that a particular radiation environment considered unacceptable for one person should also be considered unacceptable for all persons. The guidance developed for categories 2 and 3 in FRC report 7 resulted directly from this concept. For example, category 2 is concerned with the transmission of strontium-89, strontium-90, or cesium-137 to man through dietary pathways other than through milk during the first year following an acute contaminating event. This involves the use of feed crops for animals, including dairy cattle, and plant products used directly for human consumption. The intent of the guidance for category 2 is that the purpose of protective action is to prevent unacceptably contaminated produce from entering the market. The population at risk may be hypothetical and the PAG for these nuclides and crops assumes all of the crops are utilized in the immediate local area. If the contamination level is unacceptable, as derived in this hypothetical case, major contributors to the potential intake should be prevented from entering the market.

Application of the linear hypothesis is also fundamental to the concept of the dose commitment as first developed by the United Nations Scientific Committee on the Effects of Atomic Radiation. The dose commitment in this case may be defined as the mean population dose per year of practice, and has been used to evaluate the relative risk associated with activities as divergent as fallout from atmospheric testing of nuclear weapons and the significance of radiation exposure associated with medical practice.

Of the various ways in which the risk side of the projected balance may be evaluated, the FRC prefers to examine the dose commitment in relation to the basic RPG's as given in FRC report 1 and against the average dose rate associated with natural background radiation, as well as the range of dose rates occurring naturally in various occupied parts of the world. These relations allow one to gain some perspective on the significance of the practice or proposed practice in a way that allows for qualitative as well as quantitative ignorance of yet unrecognized radiation effects, and automatic weighting for various somatic effects, as well as genetic effects.

There is no known way by which the benefit side of the balance can be quantitatively evaluated in a manner made possible on the risk side through utilization of the linear hypothesis. The FRC has not adopted the often made suggestion that it should pro-rate the basic guide of 0.17 rem per capita per year on the basis of relative benefits, so that the sum of dose commitments from all activities would not exceed the basic RPG. We find this "pie cutting" approach objectionable for several reasons. The first is that the approach presumes clairvoyance regarding various applications, not now visualized, and the benefits that might be presumed to accrue from them. The second is that the RPG is not a dividing line between safety and danger so that simple compliance with the RPG itself is not an a priori justification for the degree of control exercised. Another reason is that both control capability and national need for the activity may be expected to change with time. Continuous review of national needs, as well as keeping estimates of dose commitment under surveillance, appears a more appropriate way to approach formulation of Presidential policy guidance concerned with activities resulting in human exposure.

The FRC has not developed radiation protection guidance with the specific application of the peaceful uses of nuclear explosions in mind. Under the FRC philosophy it is doubtful that a single numerical criterion applicable to all potential applications of the Plowshare type would be meaningful. Each application such as nuclear excavation, gas stimulation, and metal extraction from low grade ore involves such a diversity of benefits and potential dose commitment that a single number applicable to all would, at this time, appear to be meaningless.

The Plowshare Division of AEC in its cooperative research program with the Department of the Interior and industry is developing quantitative information on the radionuclides produced, what nuclides appear in the consumer product and in what quantities, and information on the distribution of the consumer products. An important part of this "source term" is the average release rate of nuclides such as T and ^{85}Kr to the environment per unit of time. From the laws of radioactive decay, the environmental burden will stabilize when the number of radioactive atoms decaying per unit time in the environment equals the amounts added to the environment during the same unit time.

Since both T and ^{85}Kr are by-products of other activities such as the nuclear power industry, it would appear appropriate that the addition of these nuclides from Plowshare activities be small compared to the total environmental burden from all activities. In addition to technical considerations, both legal and political considerations may become involved. For example, petroleum products with a higher than natural T/H ratio may be used for the manufacture of other products. If these uses result in the hydrogen being incorporated into food, the interpretation of the Delaney amendment by the Food and Drug Administration would have to be resolved within the FRC as an integral part of its guidance.

In summary, the development by the FRC of guidance applicable to activities such as the Plowshare program would involve an estimate of the dose commitment that might be involved, an evaluation of the national need for the resources that could be made available from the program plus possibly some legal and political considerations that could influence the particular form the guidance might take.

QUESTIONS FOR PAUL TOMPKINS

1. From Walt Kozlowski:

At what specific levels do you expect the environmental burden to stabilize? Upon reaching these levels, be they safe or unsafe, would it then become necessary to shut down the radiation sources?

ANSWER:

Well, in order to answer that question, I would have to make more assumptions than I am willing to make. First of all, you would have to pick the nuclide, you would have to pick the specific disposal type, and so forth. This will give a different answer for practically any nuclide you want to mention and I have not had occasion recently to do a check on the total environmental burden of certain nuclides, so I don't think I could honestly answer at what level I would expect any of these nuclides, such as krypton-85 for example, to stabilize. As I indicated, when you are putting in more than will be removed by decay, the level will increase. When you are putting in less than will be removed by decay, the level will decrease. The point I tried to make was in an activity such as Plowshare where it is a repetitive program and this will involve the release of certain known quantities of radionuclides, these levels, based on the frequency and the quantities, can be predicted, and one can get an advance fix on the potential dose commitment. But I would have to have the data on the number of shots per year, the number of kilotons per year, the fractions of these kilotons or megatons or whatever it is that is fission versus fusion fuel and then perhaps I could answer it.

With regard to the second part, our philosophy in so far as it is possible is to anticipate. The question of shutting down radiation sources is not the kind of question that the FRC would attach a number to. The concept involved there is that you are dealing with a danger line of go, no-go sort of operation. This may be appropriate for certain legal or regulatory applications which I am not capable of talking about, but certainly on a policy level within the Federal government it would certainly not be approached in this manner.

2. From Robert Karsh:

You have made crystal clear that when you weigh benefits against risks, everything depends upon what you put in the balance pans. How do you decide when national security and public welfare go into the same pan or into opposite pans?

ANSWER:

Well, I would answer that in two ways also. The requirements of national security are in a pan all by themselves. I think it is obvious that the nation will do things where it feels that its national security is at stake that it would not tolerate for a lesser reason. I have been personally of the conviction that weapons testing was never started because it's safe, that is not true, nor was it stopped because it's overly dangerous. The real reasons were political, strategic--many, many factors. But whenever activities involving the national security are done because of national security, there is quite often a risk side to that particular activity. Now, with regard to industrial applications, or sources that would also be sources of exposure--Plowshare, for example. There the benefit has to do with social development, the real need for power, the real need for the resource and, as I indicated, we cannot put a quantitative statement on that. In the last analysis, it becomes a high level political judgment as to when and how these two things come into coincidence.

3. From George Anton:

Please remark on the future of the benefit versus risk philosophy.

ANSWER:

I think as a philosophy it is probably not only going to remain in force, but will in fact be extended to many new activities, many environmental contamination problems that have not yet quite been so formally examined in this particular way. As a concept, I think it has a lot to offer. It has very strong deficiencies in making it easy to apply in a systematic way to a wide variety of conditions. Conventions for balancing benefit-risk in radiation or in any other activities are simply not as mathematically firm as the ICRP approach to computing the appropriate MPC's and so forth. I don't know if this really answers your question, but if your notion is that a different or more formal philosophy might replace it, I rather doubt it.

APPLICATION OF ICRP RECOMMENDATIONS RELEVANT TO INTERNAL DOSE*

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ABSTRACT

The intent of this paper is to review several of the basic concepts of radiation protection (with emphasis on internal dose) currently recommended by the International Commission on Radiological Protection (ICRP), to summarize the assumptions and methods used in the calculation of internal dose, and to illustrate by example the practical application of the pertinent guidelines.

Two broad subject areas are considered: (1) standards of radiation protection and (2) bases of internal dose estimation. Topics discussed within the framework of radiation protection standards include maximum permissible dose, categories of radiation exposure, maximum permissible dose commitment, simultaneous internal and external exposure, multiple organ exposure, and size of the exposed group. Discussion of internal dose estimation is limited to selected items that include the body burden of radionuclides and the calculation of absorbed dose, the dose equivalent, the derivation of maximum permissible concentration (MPC), the relationship of stable element intake to the MPC, and short-term and chronic exposure situations.

INTRODUCTION

The International Commission on Radiological Protection (ICRP) is an internationally recognized authority which sets values of maximum permissible exposure to ionizing radiation. Various national organizations serve a similar function in their respective countries, and in the United States this includes the National Council on Radiation Protection and Measurements (NCRP) and the Federal Radiation Council (FRC). The relatively minor differences in the recommendations of these organizations concerned with limits of permissible radiation exposures seem to reflect

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differences in the publication dates of their respective recommendations. Information contained in this paper is drawn principally from publications of the ICRP and NCRP and from selected interpretative writings of those who have served on committees of these organizations.

RADIATION PROTECTION STANDARDS

Recommendations of the ICRP are intended as guides to those responsible for radiation protection and not as codes of practice or legal regulations. These later concerns are rightfully the prerogative of national authorities. The application of radiation protection standards is intended to prevent acute radiation effects and to limit to an acceptable level the risk of such late effects as leukemia and premature aging.

Maximum Permissible Dose

The basic recommendations of the Commission are in terms of radiation doses to the whole body or to particular organs of the body. From these radiation doses are derived maximum permissible body burdens, maximum permissible intakes, and maximum permissible concentrations of radionuclides.

To some extent, exposure to any ionizing radiation entails a risk; but at permissible dose levels, this risk is believed to carry a negligible probability of severe somatic or genetic injury to an individual exposed over a long period of time.[1] Any severe somatic injury, such as leukemia, would be limited to an exceedingly small portion of the exposed group. Thus, it probably would be necessary to study large groups of individuals and use statistical methods to detect any effects at the level of the permissible doses. Faced with this difficulty, the ICRP has assumed the "linear hypothesis" - i.e., that risk is, to a first approximation, proportional to dose. Although confirmatory proof is lacking, this assumption is believed to be, if not accurate, on the conservative side.

The maximum permissible dose (MPD) is then established in light of current knowledge and attempts to balance as far as possible the risk of the exposure against the benefit of the practice.[2] Also considered is the possible danger involved in remedial actions once the exposure has occurred. The Commission's recommended maximum permissible doses are appropriate for those situations in which the levels of radiation or radioactive contamination can be controlled.

Concern is expressed by the Commission for the total intake of radionuclides by individuals in various applications of radioactive materials to be expected in the future expansion of atomic energy and for single types of population exposure that might take up a disproportionate share of the total permissible dose.[3,4] "The use of the term critical has here been extended to describe nuclides, articles of diet, and pathways of exposure which deserve primary consideration as being the mechanisms of principal exposure of individuals."[5] Clearly, it is necessary to consider multiple sources of potential radiation exposure in planning for the growth of peaceful uses of nuclear energy.

Exposure of Occupational Workers

Two changes have been made in the maximum permissible dose rate recommended for occupational exposure. In 1934, the ICRP adopted a maximum permissible dose rate of 0.2 R/day (or 1 R/week for a 5-day work week) for total body exposure.[6] This level was subsequently reduced to 0.3 rem/week in 1950[7] and to 5 rem/year (or 0.1 rem/week) in 1956.[8] Reductions in MPD did not result from positive evidence of damage due to the use of the earlier permissible dose levels. Rather, consideration was given to the lack of evidence to prove that a threshold dose existed below which no genetic or somatic damage would result and to the probability of a large future increase in radiation use as the nuclear industry expanded. The intent was to limit the genetically significant radiation exposure of the population and the probability of somatic injury by reducing lifetime doses.[9]

Values of maximum permissible dose are applied to both external and internal exposures. The present maximum permissible dose equivalents* as recommended by ICRP for occupational exposure are summarized in Table 1. Values recommended by NCRP, FRC, and the International Atomic Energy Agency (IAEA) are listed for comparative purposes.[10,11] The formula for accumulated dose, 5(N-18), where N is the individual's age in years, is intended to provide some flexibility in occupational exposure situations when the need arises. Considering the 13-week permissible exposures (Column 2) where the formula applies, it is seen that 12 rems could be accumulated in one year. However, all four authorities emphasize that workers who have accumulated a dose higher than that permitted by the formula should not be exposed at a rate higher than 5 rems/year until the accumulated dose is lower than that permitted by the formula. The formula implies that occupational exposures should not be permitted for individuals whose age is less than 18 years. However, in countries where this occupational age restriction is not limiting, the ICRP[12] and the IAEA[13] recommend that exposures to the whole body, gonads, blood-forming organs, and lenses of the eyes should not exceed 5 rems in any one year; and the accumulated dose at age 30 should not exceed 60 rems.

Columns 3 and 4 of Table 1 indicate that not all agencies have recommended specific values in each case for the annual and accumulated occupational dose. However, with the exception of the lens of the eyes, there are no differences in the recommended values. The ICRP increased the limits for the lens of the eyes to 15 rems/year and 8 rems/13 weeks since the lens does not seem to assume greater importance than other tissue from X-, gamma-, and beta-radiations.[14,15] However, for radiation of

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*Dose equivalent (rem) = absorbed dose (rad) x modifying factors. For the sake of convenience, "dose" will be used hereafter instead of "dose equivalent."

Table 1. Recommended maximum permissible dose equivalents for occupational workers.

Organ	Maximum dose equivalent (rem) in 13 weeks	Maximum permissible dose equivalent (rem) 1 year	Accumulated dose equivalent (rem)
Red bone marrow	3 - I,A,N,F	5 - I,A,N	5(N-18) - I,A,N,F
Total body	3 - I,A,N,F	5 - I,A,N	5(N-18) - I,A,N,F
Head and trunk	3 - N,F	5 - N	5(N-18) - N,F
Gonads	3 - I,A,N,F	5 - I,A,N	5(N-18) - I,A,N,F
Lenses of eyes	3 - N,F 8 - I,A	5 - N,F 15 - I,A	5(N-18) - N,F
Skin	8 - N 10 - F 15 - I,A	30 - I,N,F,A	
Thyroid	8 - N 10 - F 15 - I,A	30 - I,N,F,A	
Bone	15 - I,A	30 - I,N,A	
Hands, forearm feet, and ankles	25 - F,N 38 - I 40 - A	75 - I,N,F,A	
All other organs	5 - F 8 - I,A	15 - I,N,F,A	

F = FRC; FRC identifies its values as Radiation Protection Guides (RPG).

A = IAEA.

N = NCRP.

I = ICRP.

high linear energy transfer a lens modifying factor of 3 and a quality factor of 10 are applied.[16] For the MPD in 13 weeks there are a number of differences. The differences result from the 1960 decisions of the NCRP[17] and FRC[18] in 1966 to set for simplicity the maximum permissible quarterly values at 1/3 the annual permissible dose and of the ICRP[19] in 1966 to set the maximum permissible quarterly values at 1/2 the annual permissible dose.

It is apparent that for chronic exposure to ionizing radiation (not including planned special exposures or emergency exposures) that there are three principal ICRP regulations: (1) no more than 1/2 the annual permissible dose to any body organ in a single quarter; (2) no more than 5(N-18) rem to the organs for which the formula is applicable; and (3) no more than the annual permissible dose for the other organs.[20]

Exposure of Members of the Public

The present annual dose levels recommended by the ICRP, IAEA, NCRP, and FRC for members of the general population are listed in Table 2. With but one exception (see footnotes "d" and "e"), the values listed are 1/10 of the maximum permissible dose equivalents permitted in one year for occupational workers (see Column 3 of Table 1).[21,22] It is seen that the FRC does not have Radiation Protection Guides (RPG) for some organs. However, in his Memorandum for the President,[23] the chairman of the FRC recommended that "where no Radiation Protection Guides are provided, federal agencies continue present practices." This is taken by these authors to mean that the dose levels (and concentration guides) to be followed by federal agencies in such cases should be those recommended by the ICRP and NCRP. Thus, there appear to be no important differences among the recommendations of these authorities concerning permissible exposure levels for members of the general population.

There are a number of reasons why permissible dose levels for members of the general population should be less than those for occupational workers. According to ICRP,[24] "It is not desirable to expose members of the public to doses as high as those considered to be acceptable for radiation workers; members of the public include children who might be subject to an increased risk and who might be exposed during the whole of their lifetime; members of the public (in contrast to radiation workers) do not make the choice to be exposed, and they may receive no direct benefit from the exposure; they are not subject to the selection, supervision, and monitoring required for radiation work, and they are exposed to the risk of their own occupation."

The Commission defines a genetic dose, on the bases of the "linear hypothesis" and "no threshold" assumptions, that is relevant to an assessment of the genetic burden or genetic risk to the whole population. Specifically, they recommend that the genetic dose to the general population from all radiation sources, excluding natural background and medical sources, should not exceed 5 rems in the interval from conception to the mean age of childbearing (30 years).[25] They suggest, further, that the *annual genetically significant dose* should be the average of the individual gonad doses, each weighted by the expected number of children to be conceived after the exposure. To determine an average genetic dose for a whole population, then, it is necessary to measure or estimate not only the doses to individual members, but also to know the number of individuals exposed. Any determination or estimation of the annual genetically significant dose, in addition, requires information on the demography of the population affected.

No specific recommendations are made by the Commission as to permissible, somatically relevant doses to the population. *In cases of external* exposure of the whole body to penetrating radiation, however, the limitation imposed by the genetic dose discussed above, by itself, reduces the doses *to internal organs to or below the individual* annual dose levels listed in Table 2. The same applies to internal exposure resulting from radionuclides which contribute to the gonadal dose of a population. The previous suggestion that average concentrations of isotopes that concentrate in specific organs, other than the gonads, should not exceed 1/30 of the appropriate MPC values for continuous occupational exposure is no longer made. More recently, the ICRP indicates that those responsible for exposure of whole populations must make certain that appropriate factors are applied such that members of the critically exposed group (i.e., the group expected to receive the highest dose) do not exceed the MPD for members of the public (*Table 2*).

Size of the Exposed Group

In its earlier guidance the Commission included an illustration of how to consider the apportionment of genetic dose to various contributions.[26] Although the purpose of the example was to show how genetically significant dose depends on the number of persons exposed, the guidance was misinterpreted and hence was not included in the latest report.[27] Such guidance continues to have value in planning, especially if questions of group size are involved. But the limitations of this guidance must be recognized. The exposure situation to which the ICRP formula applies would be expected to be continuous over the extended time period involved. *Any exposure must be justified by the need for* its associated cause and not permitted simply because the expected dose would still be less than some specified level. In considering special or *one-in-a-lifetime* situations, one must keep in mind that no single type of population exposure should be permitted to take up a disproportionate share of the total dose.

The ICRP suggested that the size of the group be determined by the equation[28,29]

$$S = \frac{100\ K}{30\ I},$$

where

S = percent of total population,

K = average dose per 30 years to members of the total population as a result of exposure to the group, and

I = average dose per year to individual members of the group.

On the basis of occupational exposure at 5 rems/year total body exposure and assigning 1.0 rem for the value of K,[30] the size of the occupational group is 0.7% of the whole population; and each member of this group may accumulate 60 rems by age 30. When the entire population is considered, S, as expected, takes on the value of 100%; i.e., when K = 5 rems/30 years and I = 0.17 rem/year. Firm values of K have not been recommended, since ICRP believes the apportionment of permissible genetic dose is best left to the various countries.

Simultaneous External and Internal Exposure

Occupational exposure includes consideration of dose contributed by external and internal sources. The total dose must be controlled; initial recommendations simply considered the reduction of internal exposure by the fraction of MPD contributed by external exposure.[31] Subsequently, the Commission provided a set of rules governing the addition of doses from penetrating external exposure and exposure to long-lived bone seekers.[32] These rules are enumerated as follows: (1) No reduction need be made in maximum permissible external dose if the body burden of a radionuclide is less than one-half of the maximum permissible; (2) the total body exposure to external radiation should be reduced from 5 rems/year to 1.5 rems/year if the body burden is greater than one-half but less than the maximum permissible; and (3) the total body exposure should be reduced to zero if the body burden equals or exceeds the maximum permissible. Presumably, for simultaneous external and internal occupational exposure to short-lived radionuclides, the recommendations for quarterly and annual dose listed in Table 1 would apply.

Multiple Organ Exposure

Exposure to radionuclides released to the environment may result in dose to several organs. In those instances in which a mixture of radionuclides are taken into the body and the resultant doses in several organs are of comparable magnitude, the combined exposure is considered to constitute essentially whole body exposure.[33] The limitations imposed on occupational exposure to the gonads and the blood-forming organs then apply, and the dose to each of the organs must be restricted to not more than 3 rems/13 weeks, 5 rems/year, and an accumulated dose of 5(N-18) rem.

More recent guidance by the ICRP considers the permissible occupational exposure when several body organs are concurrently exposed.[34] If external exposure of whole body has resulted in red bone marrow or

Table 2. Annual dose levels for members of the public.

Organ or Tissue	NCRP[a] (rem)	FRC[b] (rem)	ICRP (rem)	IAEA (rem)
Gonads and red bone marrow	0.5	0.5[c]	0.5	0.5
Total body	0.5	0.5[c]	0.5	0.5
Lenses of the eyes	0.5		1.5	1.5
Other single organs	1.5		1.5	1.5
Skin, bone, and thyroid	3	1.5[d]	3[e]	3[e]
Hands, forearms, feet, and ankles	7.5		7.5	7.5

[a] These levels are based on NCRP's simple recommendation that the permissible dose to members of the population at large be reduced to not more than 1/10 of the occupational values.

[b] The FRC does not recommend Radiation Protection Guides for individual organ doses to the population other than gonads and whole body.

[c] The FRC specifies that the RPG for gonads shall be 5 rems in 30 years for average population groups on the assumption that the majority of individuals do not vary from the average by a factor greater than 3; thus, the permissible annual dose to gonads and whole body for average population groups would be 0.17 rems.

[d] The FRC recommends RPG's for the thyroid of 1.5 rems/year for individual and 0.5 rem/year to be applied to the average of suitable samples of an exposed group in the population.

[e] The ICRP and IAEA recommends 1.5 rems/year to the thyroid of children up to 16 years of age.

gonad doses in excess of 2.5 rems/year (> 1/2 MPD), no two or more organs shall be exposed at more than one-half their respective MPD (Column 3, Table 1). The dose to three or more body organs should not exceed one-half of their respective MPD.

BASES OF INTERNAL DOSE ESTIMATION

The dose actually received by man as a consequence of radionuclides released to the environment will depend upon many factors. The physical habits and characteristics of the individual (age, sex, physical condition, eating habits, hygienic standards, etc.) influence the quantity of radioactive material to which he may be exposed and the amount of material that may assimilate in various organs. Dose will also depend upon the physical and chemical properties of the radioactive material and the mode of exposure (i.e., inhalation, ingestion, puncture wound, submersion in contaminated air or water, etc.). The paucity of data to evaluate the effects of these factors on dose has made it necessary to limit the number of factors considered and to use simplifying assumptions in the calculation of body burden and maximum permissible concentrations.[35]

The principal assumptions made by the Commission in establishing the maximum permissible body burdens and the maximum permissible concentrations for occupational exposure are as follows:[36] (1) Exposure is continuous for a 50-year period to a constant level of contamination; (2) calculations are based on the so-called "standard man" whose habits and characteristics have been defined (i.e., intake rate of water and air, excretion rate, organ mass, element distribution, and biological parameters); (3) the organ is homogeneous in composition and density and the radioactive material is distributed uniformly within the organ; (4) the chemical form of a particular radionuclide is classified simply as soluble or insoluble; (5) the radionuclide is eliminated exponentially from the body organ, i.e., the fraction of organ burden eliminated per day is constant; and (6) any daughter isotopes remain present in the tissue where they are produced except for biological elimination that occurs at their characteristic elimination rates. The only modes of exposure tabulated by ICRP are inhalation and ingestion, except in a few cases where submersion in air presents the greatest hazard. The health physicist must make appropriate adjustments when population exposure situations and other exposure modes are involved.

Maximum Permissible Body Burden

The maximum permissible body burden, q, is based on that amount of the radionuclide which is deposited in the total body and produces the maximum permissible dose rate to the body organ of interest.[37] Thus, to assess the significance of an intake of radioactive material, it is necessary to know the rates of radiation dose received by the various organs and tissues of the body as a result of the deposition from that intake. The average dose rate per microcurie deposited in any part of the body is then

$$D = q \times 3.2 \times 10^{9} \times \varepsilon \times 1.6 \times 10^{-6} \times \frac{1}{100} \times \frac{1}{m}$$

$$= 51 \times q \times \frac{\varepsilon}{m} \text{ rem/day} \qquad (1)$$

where

q = microcuries accumulated in the total body,

3.2×10^{9} = number of disintegrations per day from 1 µCi,

ε = Σ EF (QF) (DF), the effective absorbed energy per disintegration, MeV (An explanation of these terms appears later in the text.),

1.6×10^{-6} = ergs per MeV,

100 = ergs per gram of tissue per rad, and

m = mass in grams of the tissue.

Two somewhat different criteria have been used by the Commission to determine maximum permissible dose values.[38] For bone-seeking radionuclides such as strontium-90 and plutonium-239, the estimate is based on a comparison with radium-226 and daughter products. Reliance has been placed on the considerable experience gained from clinical findings concerned with internally deposited radium. The maximum permissible body burden of 0.1 µg of radium-226 is considered to correspond to an average dose rate of 30 rems/year to occupational employees. For all other radionuclides the body burdens are set to limit the dose received by various organs of the body to the values listed in Column 3, Table 1.

A number of metabolic routes must be considered in internal contamination. The possible fate of radionuclides taken into the body depends on the mode of entry (inhalation, ingestion, skin absorption, or puncture wound) and on the physicochemical properties of the material (size, shape, and density of particles, and chemical form and solubility). The distribution of an ingested isotope in the body is determined by a number of factors, and these are illustrated by a simple diagram (Figure 1). For a continuous ingestion of P µCi/day, the fraction of ingested radionuclide reaching the blood is f_1 and the fraction of nuclide in the blood that reaches the critical organ is f'_2. The parameter f_2 is the fraction of the body burden in the critical organ and qf_2 is the burden of the radionuclide in the critical organ. The fraction of that taken into the body by ingestion that is retained by the critical organ, f_w, is the product of f_1, f'_2. The compartment model reflects a constant elimination rate, λ, from the critical organ. Critical organ refers to the organ of the body whose damage by the radiation results in the greatest damage to the body. Frequently, but not always, this is the organ that accumulates the greatest concentration of the radioactive material. Guidance is furnished by the Commission on appropriate values for each of these parameters in standard man as well as on the retention of particulate matter in lungs and on the contents and residence times in the gastrointestinal tract.[39,40] Possible revisions to the lung model have been considered by a Task Group of ICRP Committee 2.[14] A Task Group of ICRP

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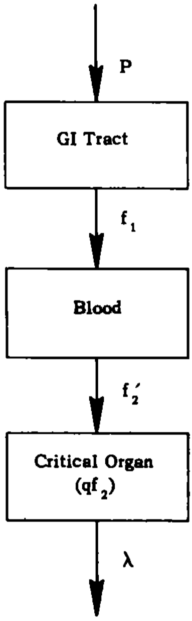
PARAMETERS CHARACTERIZING THE DISTRIBUTION
OF AN INGESTED RADIONUCLIDE



P = intake rate.

f_1 = fraction of ingested radionuclide reaching the blood.

f_2' = fraction of radionuclide in blood reaching the critical organ.

f_2 = fraction of body burden in the critical organ.

λ = fractional elimination rate.

Figure 1. Parameters characterizing the distribution of an ingested radionuclide.

Committee 4 has more recently developed the models required to calculate dose due to a short-term or acute single intake of radionuclides. Detailed information has been furnished about the metabolism of thirty-one radionuclides most frequently encountered as internal contaminants of workers.[42]

The dose equivalent in rem corresponds numerically to the product of the absorbed dose in rad by appropriate modifying factors. One of the modifying factors is the quality factor, QF (formerly referred to as RBE), which now relates to linear energy transfer (LET). Another modifying factor is the distribution factor, DF, that expresses the modification of biological effect due to non-uniform distribution of internally deposited isotopes. An example is the relative damage factor, n, applied in certain cases to the particulate component of energy (i.e., all energy other than x or γ) emitted by radionuclides deposited in the bone. Other factors in the effective absorbed energy term given above are E, the energy (MeV) absorbed per disintegration, and F, the ratio of disintegrations of daughter to disintegration of parent. Thus, insertion of the appropriate modifying factors in the effective absorbed energy germ converts the absorbed dose (rad) to the dose equivalent (rem).

The critical organ burden, Q, or the total body burden, q, is given by one of two equations.[43]

$$q = \frac{Q}{f_2} = \frac{5.4 \times 10^{-5}\ m\ R}{f_2 \varepsilon}\ \mu\text{Ci} \qquad (2)$$

$$q = \frac{Q}{f_2} = \frac{q^{Ra} f_2^{Ra}}{f_2} \times \frac{\varepsilon^{Ra}}{\varepsilon} = \frac{11}{f_2 \varepsilon}\ \mu\text{Ci} \qquad (3)$$

Equation (2) follows from equation (1) when R is the dose rate in rem/year, and it applies to all organs except bone. Equation (3) applies in the case of α- and β-emitting radionuclides that localize in the bone and relates the maximum permissible body burden to a permissible bone burden of 0.1 μCi of radium-226. The constant in this equation is derived from the permissible body burden of radium-226 (0.1 μCi), the fraction of radium-226 in the bone of that in the total body (0.99), and the effective absorbed energy of radium-226 and its daughter products (110).

Maximum Permissible Concentrations

Maximum permissible comcentrations (MPC) for all organs other than the GI tract are computed on the basis of a constant level of exposure and the single exponential model leading to the equation[44]

$$\frac{dQ}{dt} = P - \lambda Q \qquad (4)$$

The solution of this equation when Q = 0 at t = 0 is

$$Q = qf_2 = \frac{P}{\lambda}(1 - e^{-\lambda t}) \tag{5}$$

when

λ = effective decay constant = $\frac{0.693}{T}$;

T = effective half-life $(T_r T_b)/(T_r + T_b)$, days;

T_r = radioactive half-life, days;

T_b = biological half-life, days;

t = exposure period (taken as 50 years for occupation exposure), days;

P = rate of uptake of the radionuclide by the critical body organ, µCi/day.

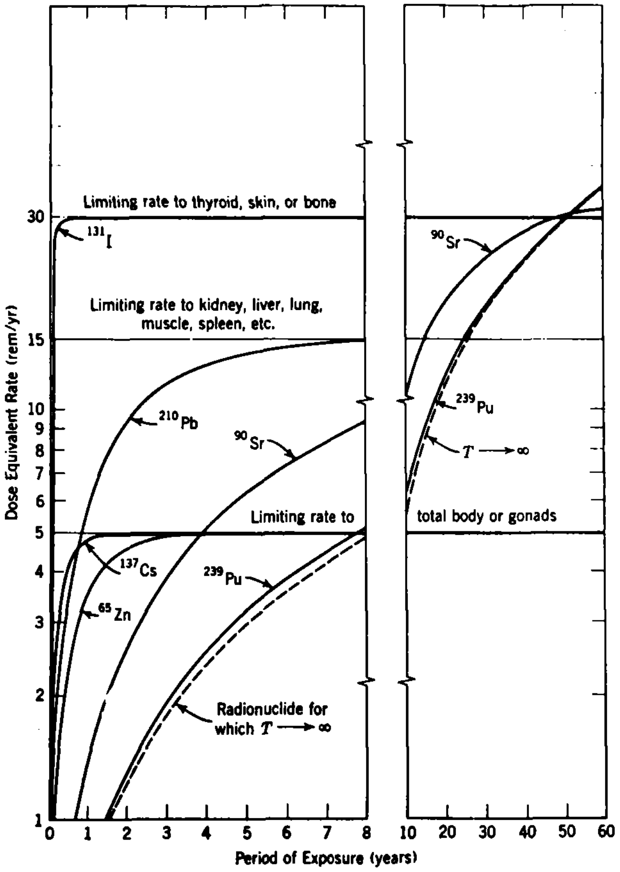
The amount of material deposited in the critical organ is equal to the product of the concentration of the radionuclide in air or water taken into the body, M(µCi/cm^3), the average rate of intake, I(cm^3/day), and the fraction of the radionuclide initially retained in the critical organ, f_a, or f_w. Thus P = MIf. For occupational exposure at the MPC of the radionuclide in water, M = $(MPC)_w$ and in air, M = $(MPC)_a$.

It is clear from equation (5) that the body burden and the associated dose rate increase throughout the exposure period, which is taken as 50 years for occupational exposure. By substituting appropriate values of P in equation (5), the expression for maximum permissible concentration is

$$MPC = \frac{cQ}{Tf(1-e^{-\lambda t})} \tag{6}$$

in which c = 10^{-7} for inhalation and c = 9.2×10^{-4} for ingestion of water when the MPC is for occupational exposure of 40 hours per week.[45] It is usually assumed that standard man consumes half his daily intake as air and water during the 8-hour working day. For continuous occupational exposure the MPC values should be divided by 2.92, except for submersion as the exposure mode where they should be divided by 4.38 to correct for intake and occupancy factors. Equation (6) can be modified for parent-daughter radionuclides and for the GI tract as the critical organ.[46]

For internal exposure the pattern of dose delivered at the MPC is illustrated for a few radionuclides in Figure 2. The permissible dose rate for a particular organ (Column 3, Table 1) is attained after an occupational exposure at the constant MPC value for 50 years. Theoretically, although a constant dose rate is never achieved with continuous



Plot of dose equivalent versus years of exposure at the constant level of MPC.

Figure 2. Plot of dose equivalent versus years of exposure at the constant level of MPC.

deposition, 99% of the equilibrium value is reached after a time period corresponding to six effective half-lives. The intake of iodine-131 with an effective half-life of 7.6 days will reach an equilibrium thyroid burden and a dose rate of 30 rems/year to the thyroid after about 7 weeks' exposure at the MPC. For radionuclides such as strontium-90 and plutonium-239 with long effective half-lives, 100% of the permissible occupational dose rate is reached after 50 years of exposure at the MPC but, in the case of strontium-90, only 86% of the bone burden is reached. The fact that the dose rate after 50 years of exposure may exceed the permissible rate is not viewed with alarm, since few, if any, workers will be so exposed. Although the permissible dose rate for very long-lived radionuclides is only achieved after 50 years of exposure, any safety factor is more apparent than real. In practice, individual workers are likely to be exposed for only a few years early in their work experience, and the permissible dose commitment will, in fact, be nearly achieved.

The most recent guidance on MPC values for strontium-90 considers that metabolic data provide a sounder basis for the estimation of MPC values than the exponential model used previously in the recommendations.[47] "Extensive experimental data indicate that the strontium-calcium ratio of mineral derived from diet in newly formed bone is about 0.25 of the corresponding ratio in the normal human diet. Data are also available on the average concentrations of stable strontium and stable calcium in normal human diet and bone of large populations." There was no change made in the permissible body burden of strontium-90, but the MPC values for bone as the critical organ were increased by a factor of 4, and the MPC values for total body as the critical organ were increased by a factor of 2.

Maximum Permissible Dose Commitment

The MPC or MPI are satisfactory concepts from the standpoint of more or less continuous exposures. Only recently has the ICRP provided detailed guidance on single exposures to radionuclides inhaled or ingested, and it emphasized the problem associated with rapid buildup in the body of radionuclides having long effective half-life.[48] An occupational worker who acquires a bone burden of strontium-90 such that the dose of 15 rem is received during 13 weeks of the year, following a single exposure or quarterly exposure, will continue to receive a bone dose of this magnitude for many years thereafter. Thus, the worker would be restricted to work in environments that add little, if any, additional exposure.

To avoid the possible restriction of an employee's activity, the ICRP has introduced the concept of maximum dose commitment. An annual maximum dose commitment is the dose resulting from the intake of radionuclides corresponding in amount to intake at the MPC for 1 year. Figure 3 illustrates the application of the concept of maximum permissible dose commitment.[49] Curve A represents the dose rate to the critical body organ as a function of time, t, following a single short-term intake of time, τ, of a radionuclide. It is a maximum permissible dose commitment

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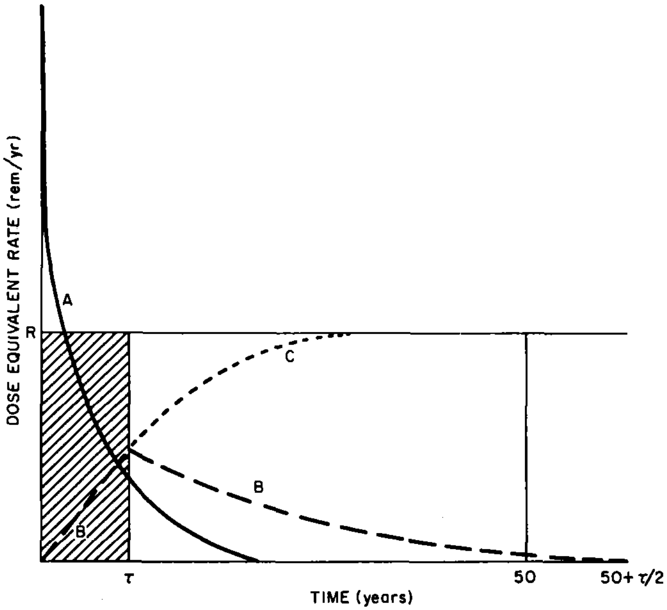

Figure 3. Curves illustrating the maximum permissible dose commitment concept.

if the area under this curve (integrated dose) from $t = 0$ to $50 + \tau/2$ years is equal to the area under curve B for this same period. Curve B represents the dose rate to this same body organ when the person is occupationally exposed to the MPC of a radionuclide for a period γ years. If $\tau = 1/2$ year, the exposure is the maximum permissible dose for single exposures or for exposures on a quarterly basis. In every category of maximum permissible dose commitment, the area under curve A equals area under curve B equals $R\tau$, the area of the rectangle in which R is the maximum permissible dose rate appropriate to the critical body organ for the radionuclide as given in Column 3 of Table 1. For any exposure at the MPC the dose rate approaches the value R, as shown by the dotted curve C, and in every case reaches the value R at or before 50 years.

The concept of dose commitment has application where members of the public may be exposed. An earlier study made use of this approach in the assessment of the safety of waste releases to the Clinch River at Oak Ridge National Laboratory,[50] and a paper to be given at this conference illustrates another application.[51]

Single or Short-Term Exposure

The ICRP has indicated that up to one-half of the maximum permissible dose commitment may be accumulated in a quarter of a year.[52] These commitments may be taken in any pattern during the quarter interval, from single, near instantaneous exposures to continuous exposures. In the case of internal exposure to radionuclides having short effective half-lives, this corresponds to a quarterly dose at twice the dose rate permitted on an annual basis, or to receiving one-half the annual dose in 13 weeks. For internal exposure to radionuclides having a long effective half-life, this corresponds to a total intake of the radionuclide equal to one-half of that which would be permitted for continuous exposure at the MPC for 1 year. The dose equivalent over a 50-year period would numerically equal one-half of the annual permissible dose. This relationship between dose from a single or short-term exposure and dose from continuous exposure has been demonstrated by K. Z. Morgan.[53]

Consideration of Stable Element Intake

Many factors have an effect in determining the value for a maximum permissible limit. One such factor is the relative abundance or scarcity in the diet of stable isotopes with similar chemical properties of the radionuclide.[54] When data are lacking on the metabolism of a particular radionuclide in the human body, as is frequently the case, information on the intake and elimination of stable isotopes of the element in the critical body organ may be used in the calculation of permissible levels. It is assumed that the distribution of the normal stable isotope in the body organs is typical of the distribution that would result from chronic exposure to radionuclides of the same element and that an equilibrium condition exists between the stable isotope in the body organ and in the dietary intake. When this is the case, it follows that for a stable isotope[55]

$$T_b = \frac{0.693\ m\ C}{I f_w} \qquad (7)$$

where

m = mass in grams of the tissue,

C = average concentration of the element in the critical organ (grams of element per gram of wet tissue),

I = average daily ingestion of an element (g/day), and T_b and f_w are as defined previously.

By substituting equation (7) in equation (5) for an equilibrium situation and letting $P = I^* f_w$ (where I^* is equal to the permissible intake of the radionuclide, or $(MPC)_w$ times the standard man intake of water), it can be shown that

$$\frac{qf_2}{\text{g element in organ}} = \frac{I^*}{I}\left[\frac{T_r}{\frac{0.693\ m\ C}{I f_w} + T_r}\right] \qquad (8)$$

Values of $(MPC)_w$ *calculated from equation (8) will then correspond to* similar values listed in ICRP Publication 2 for cases where stable element data was judged to be acceptable and was used to calculate maximum permissible concentrations. Thus, it can be seen that the Commission considered stable element intake in its derivation of maximum permissible concentrations.

REFERENCES

1. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (as amended 1959 and revised 1962), ICRP Publ. 6, p. 9, Pergamon Press, London (1964).

2. Ibid, p. 10

3. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (adopted September 17, 1965), ICRP Publ. 9, p. 12, 15, Pergamon Press, London (1966).

4. ICRP Publ. 6, op cit, p. 26.

5. International Commission on Radiological Protection, Principles of Environmental Monitoring Related to the Handling of Radioactive Materials (Report of Committee 4), ICRP Publ. 7, p. 9, Pergamon Press, London (1966).

6. L. S. Taylor, "History of the International Commission on Radiological Protection (ICRP)," Health Physics 1, 97 (1958).

7. Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units--1950, National Bureau of Standards (US) Handbook 47 (1951).

8. International Commission on Radiological Protection, "Report on 1956 Amendments to the Recommendations of the International Commission on Radiological Protection (ICRP)," Radiology 70, 261 (1958).

9. ICRP Publ. 6, op cit, pp. 17, 18, 26.

10. International Atomic Energy Agency, Basic Safety Standards for Radiation Protection, Safety Series Publ. 9, p. 9, Vienna (1962).

11. K. Z. Morgan, "Present Status of Recommendations of the ICRP, NCRP, and FRC," presented at the Health Physics Society Meeting in Los Angeles, June 14, 1965; to be published in Progress in Nuclear Energy Series XII, Vol. 2, Pergamon Press, London.

12. ICRP Publ. 9, op cit, p. 9.

13. IAEA Publl. 9, op cit, p. 17.

14. ICRP Publ. 6, op cit, p. 9.

15. ICRP Publ. 9, op cit, p. 10.

16. Morgan, "Present Status of Recommendations of the ICRP, NCRP, and FRC," *op cit*, p. 8.

17. "Maximum Permissible Body Burden and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," *National Bureau of Standards (US) Handbook* 69 (1959).

18. Federal Radiation Council, *Background Material for the Development of Radiation Protection Standards*, Report No. 1, U. S. Government Printing Office, Washington, D. C. (May 1960).

19. ICRP Publ. 9, *op cit*, p. 10.

20. K. Z. Morgan and J. E. Turner (ed.), *Principles of Radiation Protection*, p. 511, John Wiley and Sons, Inc., New York (1967).

21. Federal Radiation Council, *Background Material for the Development of Radiation Protection Standards*, Report No. 2, p. 9, U. S. Government Printing Office, Washington, D. C. (Sept. 1961).

22. ICRP Publ. 9, *op cit*, p. 13.

23. A. S. Fleming, "Radiation Protection Guidance for Federal Agencies," *Federal Register*, p. 4402 (May 18, 1960).

24. ICRP Publ. 9, *op cit*, p. 8.

25. *Ibid*, p. 15.

26. ICRP Publ. 6, *op cit*, p. 31.

27. ICRP Publ. 9, *op cit*, p. 16.

28. ICRP Publ. 6, *op cit*, p. 32.

29. Morgan, *Principles of Radiation Protection*, *op cit*, p. 517.

30. ICRP Publ. 6, *op cit*, p. 32.

31. International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection (Report of Committee 2 on Permissible Dose for Internal Radiation)*, ICRP Publ. 2, Pergamon Press, London (1959).

32. ICRP Publ. 6, *op cit*, p. 15.

33. *Ibid*, p. 29.

34. ICRP Publ. 9, *op cit*, p. 12.

35. ICRP Publ. 2, *op cit*, p. 6.

36. *Ibid*, p. 8.

37. *Ibid*, p. 10.

38. *Ibid*, p. 11.

39. ICRP Publ. 6, *op cit*.

40. ICRP Publ. 2, *op cit*.

41. ICRP Task Group on Lung Dynamics (P. E. Marrow, chairman), "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," *Health Physics* **12**, 173 (1966).

42. ICRP Task Group of Committee 4 (G. C. Butler, chairman), *Evaluation of Radiation Doses to Body Tissues from Internal Contamination Due to Occupational Exposure* (in press)

43. ICRP Publ. 2, *op cit*, pp. 13, 15.

44. *Ibid*. p. 16.

45. *Ibid*, p. 16.

46. *Ibid*, p. 17.

47. ICRP Publ. 6, *op cit*, p. 39.

48. ICRP Publ. 9, *op cit*, pp. 10, 12.

49. K. Z. Morgan, "Assumptions Made by the Internal Dose Committee of the International Commission on Radiological Protection," paper presented at Sixth Annual Meeting of the Gesellschaft fur Nuclear Medizin, Wiesbapen, Germany, September 26-28, 1968.

50. K. E. Cowser, W. S. Snyder, *et al*., "Evaluation of Radiation Dose to Man from Radionuclides Released to the Clinch River," *IAEA Symposium on Disposal of Radioactive Wastes Into Seas, Oceans, and Surface Waters, Vienna, Austria*, p. 639 (1966).

51. S. V. Kaye and P. S. Rohwer, "Methods of Estimating Exposures to Populations from Plowshare Applications," paper presented at Symposium on Public Health Aspects of Peaceful Uses of Nuclear Explosives, Las Vegas, Nevada, April 7-11, 1969.

52. ICRP Publ. 9, *op cit*, p. 10.

53. Morgan, *Principles of Radiation Protection*, *op cit*, p. 324.

54. ICRP Publ. 2, *op cit*, p. 27.

55. ICRP Publ. 2, *op cit*, p. 33.

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DEVELOPMENT OF REGULATORY CRITERIA APPLICABLE TO CONTROL OF RADIATION EXPOSURES TO THE POPULATION FROM PRODUCTS CONTAINING RADIOACTIVE MATERIAL

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ABSTRACT

Under the Atomic Energy Act of 1954, as amended, the Atomic Energy Commission is responsible for regulating the possession, use and transfer of byproduct, source and special nuclear materials in accordance with safety standards established by rule of the Commission to protect health and minimize danger to life and property. This paper describes some of the basic considerations in establishing safety criteria and regulations for authorizing the transfer and use of byproduct material (radioisotopes) in products for distribution to the general public. It discusses problems encountered in extending the broad guidance provided by the Federal Radiation Council (FRC) and by the International Commission of Radiological Protection and the National Council on Radiation Protection and Measurements (ICRP-NCRP), which is limited to total exposures of individuals and population groups to radiation from many sources, to appropriate controls on radioactivity in an individual consumer product which represents only one source of population exposures. The paper also discusses possible approaches to accomplishing the regulatory objectives of providing reasonable assurance that (1) the contribution of an individual product to total exposures that might be permitted under FRC and ICRP-NCRP guidance should not be disproportionate to the benefits to be derived, and (2) appropriate efforts are made to limit exposures to the population from individual classes of sources of exposure as far as *practicable. Existing criteria and regulations pertaining to the control of radiation exposure to the population from products into which radioactive material is purposely introduced are described, and additional considerations which must be taken into account for the development of further criteria and regulations which are applicable to the possible wide-scale distribution of products containing radioactive material as a result of the Plowshare Programs are explored.*

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Previous speakers have described experimental Plowshare projects designed to determine the feasibility of using nuclear explosives to aid in the production of products such as natural gas, oil and copper. The Atomic Energy Commission recognizes that in evaluating the feasibility of such uses of nuclear explosives, criteria and controls for protection of the health and safety of the public using the products are of primary importance. A key factor is to minimize the amount of residual radioactivity that may become associated with the products. It is for this reason that major objectives of the Plowshare program are to develop information that will assist in the determination of exposures to the public from the use of products produced by nuclear explosives and to investigate means of reducing the amount of radioactivity associated with the product. This information will permit the progressive and timely development of regulations which are related to the specific conditions prevailing at the various stages of development of the use of nuclear explosives.

Even for the most advanced project, the production of natural gas by nuclear stimulation, it is too early to support detailed suggestions as to regulations which might be imposed on wide-scale uses of such products. The purpose of this paper is to discuss some of the general considerations in the future development of regulations applicable to commercial distribution of natural gas and other products that might be produced with the aid of nuclear explosives.

The distribution on a commercial scale of products such as natural gas, oil and copper to be produced by nuclear explosives involve factors that differ in many respects from those that have been taken into account by the Atomic Energy Commission in its present regulations.

Exemptions from regulatory control of various products that have been established by the Atomic Energy Commission were not developed with Plowshare-produced products in mind and cannot be considered to be directly applicable to such products. However, there are many factors, which have already received extensive consideration by the Atomic Energy Commission in controlling the distribution to the general public of other products containing radioactive material, that are also pertinent to the development of regulations for the control of Plowshare products. It is useful at this point to review these common factors.

Basic considerations for the development of criteria and regulations designed to protect the public health and safety, including those related to authorizing the use of consumer products containing radioactive material exempt from regulations, are contained in the recommendations of the International Commission on Radiological Protection, the National Council on Radiation Protection and Measurements, and the Federal Radiation Council. (These groups are commonly known as the ICRP, the NCRP, and the FRC, respectively.) In summarizing quantitative recommendations of these groups for limiting exposures of the general public to radiation, we shall use the term, Radiation Protection Guide, adopted by the FRC. The corresponding term adopted by the ICRP is Dose Limit.

Quantitative recommendations of the ICRP, NCRP and FRC establish Radiation Protection Guides for limiting exposures of the general public to radiation. For individual members of the general public, the Radiation Protection Guide for whole-body exposures is one-half rem per year. Corresponding Guides for limited portions of the body are higher by factors that range from 3 to 15. For the total population, it is recommended that the average genetically effective exposure should not exceed 5 rems in 30 years. For the present purpose, the most pertinent Radiation Protection Guide established by the FRC provides that as an operational technique, where the individual whole-body doses are not known, a suitable sample of the exposed population should be developed whose protection guide for annual whole-body dose will be 170 mrem per capita per year. These exposure guides do not include either exposures to radiation from naturally-occurring sources or exposures to radiation from medical procedures.

Both the ICRP and the FRC consider that the primary purpose of Radiation Protection Guides for individual members of the general public is to provide guidance for limiting levels of radiation and radioactivity in man's environment and recognizes that it may not always be practical to assure that there will not be some individuals who will receive greater exposures than specified in the guide. For example, in paragraph 70 of its Publication 9, the ICRP states:

> "The Maximum Permissible Doses that have been established for occupational (emphasis supplied) exposure are regarded as upper limits, and the doses may have to be individually monitored and controlled to ensure that the Maximum Permissible Doses are not exceeded. The dose limitation for members of the public is a more theoretical concept, intended to provide standards for the design and operation of radiation sources so that it is unlikely (emphasis supplied) that individuals in the public will receive more than a specified dose. The effectiveness of this is checked, not by observing individuals, but by assessments through sampling procedures in the environment and statistical calculations, and by a control of the sources from which the exposure is expected to arise..."

Both the ICRP and FRC use these individual Radiation Protection Guides to develop alternative recommendations for controlling exposures from radioactivity in the environment, expressed in terms of average exposures of selected groups of individuals. While these alternative recommendations better reflect the nature of the environmental standards of radiation protection, lack of precise criteria for selecting groups of individuals over which averages should be taken make them difficult to apply. The ICRP, after discussing the selection of appropriate groups, concludes (paragraph 74):

> "Because of the innate variability with an apparently homogeneous group, some members...will receive doses somewhat higher than the Dose Limit. However, at the very low levels of risk implied, it is likely to be of minor consequence to their health if the Dose Limit is marginally or even substantially exceeded."

The ICRP further observes (paragraph 75) that:

> "In some situations...it may not be practical to make the detailed studies necessary for the identification of the critical group. To allow for individual variability it will then be necessary to apply an operational 'safety factor' to the derived concentration limits applicable to a member of the public. ...However, as the values to be recommended for such factors

> would vary over a wide range, depending on the particular circumstances, no generally applicable values are given in this report."

Qualitatively, the ICRP, the NCRP, and the FRC generally recommend that, within Radiation Protection Guides, exposures to radiation be kept as low as practicable. The ICRP adds (paragraph 87):

> "...that it is important to ensure that no single type of population exposure takes up a disproportionate share of the total. The way in which this is done will depend upon circumstances which may vary from country to country, and will be determined by national, economic and social considerations."

Recommendations of the FRC, like those of the ICRP, which we have just quoted, are based on the nature of the risks to health of radiation exposure which have been discussed by Dr. Tompkins.

Considerations such as these led the Federal Radiation Council to include, in its first recommendations on radiation protection guidance, approved by the President May 13, 1960, the following general recommendations on the use of the Radiation Protection Guides:

> "It is recommended that:
>
> 1. There should not be any man-made radiation exposure without the expectation of benefit resulting from such exposure. Activities resulting in man-made radiation exposure should be authorized for useful applications provided recommendations set forth herein are followed.
>
> 2. The term 'Radiation Protection Guide' be adopted for Federal use. This term is defined as the radiation dose which should not be exceeded without careful consideration of the reasons for doing so; every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable.
>
> 3. ● ● ● ● ● ●
>
> 5. There can be no single permissible or acceptable level of exposure without regard to the reason for permitting the exposure. It should be general practice to reduce exposure to radiation, and positive effort should be carried out to fulfill the

> sense of these recommendations. It is basic that exposure to radiation should result from a real determination of its necessity.
>
> • • • • • • •
>
> 7. The Federal agencies apply these Radiation Protection Guides with judgment and discretion, to assure that reasonable probability is achieved in the attainment of the desired goal of protecting man from the undesirable effects of radiation. The Guides may be exceeded only after the Federal agency having jurisdiction over the matter has carefully considered the reason for doing so in light of the recommendations in this paper."

It is within this framework that the AEC, as a regulatory agency, works in developing appropriate criteria, standards and regulations governing the control of sources of exposures to the population from atomic energy activities, including the distribution of consumer products containing radioactive materials. Simply stated, the AEC objectives in developing safety criteria are to provide reasonable assurance that:

> (1) appropriate efforts are made to limit exposures to the population from individual classes of "sources-of-exposure" as far as practicable;
>
> (2) the exposures of the general public to ionizing radiation from all sources will not exceed levels recommended by the Federal Radiation Council and approved by the President; and
>
> (3) the contributions of individual classes of "sources-of-exposure" to exposures of the public are not disproportionate to their net contributions to the national welfare.

In undertaking to meet these objectives, we find that different classes of "sources-of-exposure" involve considerations that require different regulatory controls and specific criteria for limiting their respective contributions to exposure of the public to radiation. Whenever an activity or a product that constitutes a new "source-of-exposure", or a substantial modification of an existing one, is proposed, it becomes necessary to review existing regulatory requirements to determine what modifications may be desirable to assure that our objectives will continue to be met.

In considering the development of criteria and controls to limit exposures of the public to radiation from byproduct material contained in consumer products, it may be observed at the outset that it will generally not be practical to achieve AEC objectives by regulating users of the product. Not only would the effort required to effectively regulate the user be expected to outweigh the reasons for introducing the byproduct material into the product, but the impact on the user would generally be unacceptable to him. Consequently, our interest is in the development of criteria for determining whether or not the characteristics of a particular product sufficiently limit its potential for exposure of members of the public to justify exemption of its use from regulatory control. Assurance that an exempt product meets specified requirements must then depend upon regulations applicable to the producer, importer, or distributor of the product.

In practice, the manufacturer or importer of a product containing byproduct material is prohibited from transferring the product for distribution to the public unless the product is shown to meet the requirements established in a specific license which authorizes the distribution.

The Commission has developed general criteria for exempting the use of byproduct material in products that depend on the radioactivity to perform a useful function, as in the case of self-luminous products. These criteria appear in the Federal Register of March 16, 1965. The key provisions of these criteria are:

> "2. Approval of a proposed consumer product will depend upon both associated exposures of persons to radiation and the apparent usefulness of the product. In general, risks of exposure to radiation will be considered to be acceptable if it is shown that in handling, use and disposal of the product it is unlikely that individuals in the population will receive more than a small fraction, less than a few hundredths, of individual dose limits recommended by such groups as the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the Federal Radiation Council (FRC), and that the probability of individual doses approaching any of the specified limits is negligibly small. Otherwise, a decision will be more difficult and will require a careful weighing of all factors, including benefits that will accrue or be denied to the public as a result of the Commission's action. ..."

"9. In evaluating proposals for the use of radioactive materials in consumer products the principal considerations are:

(a) The potential external and internal exposure of individuals in the population to radiation from the handling, use and disposal of individual products;

(b) The potential total accumulative radiation dose to individuals in the population who may be exposed to radiation from a number of products;

(c) The long-term potential external and internal exposure of the general population from the uncontrolled disposal and dispersal into the environment of radioactive materials from products authorized by the Commission; and

(d) The benefit that will accrue to or be denied the public because of the utility of the product by approval or disapproval of a specific product."

"1. At the present time it appears unlikely that the total contribution to the exposure of the general public to radiation from the use of radioactivity in consumer products will exceed small fractions of limits recommended for exposure to radiation from all sources. Information as to total quantities of radioactive materials being used in such products and the number of items being distributed will be obtained through record-keeping and reporting requirements applicable to the manufacture and distribution of such products. If radioactive materials are used in sufficient quantities in products reaching the public so as to raise any question of population exposure becoming a significant fraction of the permissible dose to the gonads, the Commission will, at that time, reconsider its policy on the use of radioactive materials in consumer products."

These criteria were intended to be specifically applicable only to products into which radioactive material is incorporated for the purpose of performing a useful function as part of the product such as its use in self-luminous devices. While the criteria may provide some guidance on an approach to development of criteria for Plowshare products, there are many new factors introduced in the use of products produced by nuclear explosives such as the type of the product; the nature of the processing and distribution systems; the critical pathways of exposure to man; and the type and size of population groups that will use the various products.

Safety criteria and conditions of exemption specifically applicable to each Plowshare-produced product should take into account considerations such as the following:

(1) The contribution of the Plowshare-produced product to the national welfare.

(2) The feasibility of limiting radioactive contamination of the product, as released by a licensed producer or processor, to acceptable levels.

(3) Possible and probable exposures to individuals and population groups as a result of exemption of the product from regulation under specified conditions.

Among proposals to use nuclear explosives for the commercial production of various products, only the proposal for use in the production of natural gas is in an advanced stage. Project Gasbuggy and future Projects Rulison and Dragon Trail are designed to provide information on the feasibility of commercial production of natural gas by this means. These experiments should provide much of the information needed to formulate controls on the distribution of gas and conditions under which use of the gas might be exempted from regulation. Additional studies will be required to provide information on matters such as methods of reducing the amount of byproduct material in gas to the extent practicable and relationships between concentrations of gas introduced into various collection and distribution systems and resultant exposures of persons and groups of persons.

Without attempting in any way to prejudge the results of data collection and evaluation effort that is really just beginning, I thought you might find it instructive if I were to sketch out what appears to be a likely way for regulations to evolve. I would expect us to feel our way through several stages of development of criteria and controls as gas from test wells is introduced into distribution systems in an increasing amount as information is developed about the concentration of byproduct material in Plowshare-produced gas and how that gas moves about in distribution systems.

It seems reasonable in the first place that certain points of control in a gas distribution system would be specified beyond which the further distribution and use of the gas would be free of regulation, or, if you will, the gas would then be an exempt consumer product. As in the transfer and distribution of other exempt consumer products, the person introducing the gas into the distribution system would be required to meet such limits on the radioactive content of the gas as might be determined by the Commission to be necessary for the protection of the public health and safety.

The limits on maximum concentrations of radioactivity in the gas would be applied at specified points of control in the distribution system. These limits would be derived from criteria for acceptable levels of radiation exposure to a suitable sample of exposed population groups using natural gas or products produced from gas at various stages in the distribution system. In deriving the limits it would be necessary to take into consideration the radionuclide and its chemical form, the dilution afforded in the distribution or processing system prior to the first point of use of the gas, the nature of the use of the gas (i.e., home uses, manufacturing of products, industrial heat, etc.), and the relationship between concentrations in the gas or product at the point of use and exposures to people. For example, if gas were used for industrial heat to generate power where combustion products would be vented through a stack, the concentrations of radioactivity that could be permitted would probably be substantially higher than if the gas were used for cooking or nonvented heating in the home.

The criteria for acceptable levels of exposure to a suitable sample of exposed population groups must of course be compatible with both the quantitative and qualitative recommendations of the Federal Radiation Council. This means that the concentration of byproduct material in natural gas should be reduced to the extent practicable. In view of the increasing importance of other sources of exposure to ionizing radiation, the contribution of byproduct material in exempt natural gas produced by nuclear stimulation should not take up a disproportionate share of total exposures of the public to radiation from all sources. It is too early at this time to estimate what that share might be.

We do not believe it will be appropriate or reasonable to establish a single limit, that is applicable to all situations, in terms of either concentrations of radioactivity introduced into a distribution system or limits on radiation exposure to the public. For example, we suspect that it will be desirable in the developmental phase of the production of natural gas by nuclear stimulation to carry out tracer experiments in distribution systems using some of the gas produced in experimental projects. Such experiments would be useful in developing data on such items as the behavior of gas in distribution systems, dilution factors, and critical pathways of exposure to man that are essential to the development of limits. The limits on concentrations of byproduct material permitted to be introduced into a pipeline distribution system for such tracer experiments could, of course, be substantially higher than limits on large volumes of gas produced by nuclear stimulation for ultimate distribution on a commercial basis.

It is likely that the regulatory controls which will initially be imposed on the introduction of gas into commercial channels will differ from those used at a later time when the technology has been more fully developed, pathways of exposure and affected population groups have been better identified, and the accuracy of theoretical exposure models has been confirmed by field assessment. As the commercial production phase is fully realized, it is possible that both the methods and specific requirements for control will vary from one gas field to another to achieve common objectives in limiting exposures. This could result from important differences among gas fields and the areas they supply, such as differences in composition of the gas, production rates, collection and distribution systems, and a difference in size or nature of consumer groups using the gas.

There are, of course, many questions that will have to be resolved as the Plowshare nuclear stimulation projects move forward. For example, how should the exposure criteria and limits be related to the total volume of gas produced by nuclear stimulation as compared to the total volume produced by conventional means particularly as this ratio increases with the use of the nuclear stimulation technique? How do we determine all of the important pathways of exposure and take into account the variation in exposure among users of the gas? The AEC is depending upon the information and data being developed in the Plowshare experimental program to assist in answering some of these questions and to serve as the basis for formulating those controls necessary for the protection of public health and safety. I would like to point out that any proposed regulations that would be developed would, of course, first of all be reviewed at the highest level in the Commission and would then be published for public comment before being put into effect.

The criteria and controls for authorizing the distribution and use of other products which may be produced as a result of the Plowshare program will probably differ from those which will be developed for regulating the distribution and use of natural gas produced by nuclear stimulation. However, the basic approach discussed in this paper would probably be about the same.

QUESTIONS FOR LESTER ROGERS

1. From George Anton:

Since the benefit in the risk versus benefit consideration is not really measureable, is not the actual interim practice in establishing criteria a matter of minimizing practicable exposures for the activity being considered?

ANSWER:

I think the answer to that question is yes. It is a matter of minimizing practical exposures for the activity that is being considered. Of course once you minimize it, one then has to evaluate what likely exposure there is to be and then a decision has to be made on the basis of that benefit-risk balance.

2. From Charles Hardin:

Would you care to comment on the question of jurisdiction or regulatory responsibility for radionuclides released into consumer products from Plowshare Projects, when such Projects are conducted in Agreement States?

ANSWER:

I'll be glad to comment on this. I think we should hold in mind the comment I made at the beginning of my paper and that is to the effect that the question of just how the regulatory pattern will develop for Plowshare is somewhat of an open question. But I will answer in light of the present regulatory relationship between the Agreement States and the Atomic Energy Commission. Now for those of you who do not understand what the Agreement State Program is, in 1954 under the Atomic Energy Act, the Atomic Energy Commission was given its responsibility for the regulating of all types of atomic energy activities. There was some question about the role of states in this area and in 1959, there was an amendment to the Atomic Energy Act, Section 274, which authorized the Commission to relinquish its regulatory responsibilities for bi-product materials, source materials, quantities of special nuclear material less than a critical mass, when the governor of a state certified or entered into an agreement with the Commission. There were certain activities which were reserved by the Commission, including the regulation of the production utilization facilities, nuclear power reactors. One other area that was reserved by the Commission was to regulate the transfer of products intended for use by the general public when this transfer was made by manufacture in an Agreement State. Now the Commission's regulatory responsibility for the transfer of products by manufacture in an Agreement State is limited to the safety of the product itself and the manufacturer must have a license from the Atomic Energy Commission to transfer that product. The in-plant safety, the manufacturing of that product, is a responsibility of the Agreement State. So under the present regulatory relationship, the Atomic Energy Commission would regulate the release of Plowshare products by the manufacturer and the manufacturer would need a license from the Atomic Energy Commission in order to release that product in Agreement States as well as in Non-Agreement States.

PLOWSHARE RADIATION PROTECTION GUIDANCE

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ABSTRACT

The recommendations of the ICRP and the NCRP were developed primarily for occupational radiation exposures. They were later modified and applied to non-occupational exposures of populations. These, with appropriate interpretations, can be used to provide Plowshare radiation protection guidance.

Exposures from Plowshare operations will tend to be acute, arising from radionuclides of relatively short half-life, but will have some chronic aspects due to small amounts of long-lived radionuclides generated. In addition, the neutron activation process of Plowshare technology will produce radionuclides not commonly encountered in routine nuclear energy programs.

How these radionuclides contribute to personnel exposure is known for only a few situations that may not be representative of Plowshare exposure. Further complications arise from differences in radionuclide deposition and physiological sensitivity among individuals of different ages and states of health in the exposed population. All parameters necessary to evaluate such exposures are not available, even for good quantitative approximations, resulting in the need for interpretive experience.

INTRODUCTION

Nuclear energy has shown us its destructive forces in war, its harnessed powers in electrical generating facilities, its humane potentials in medicine, and most recently, its constructive capabilities in Plowshare programs. Are the radiation protection aspects of Plowshare applications ready to meet the needs of the rapidly developing programs? A look at the radiation protection guidance currently on hand says yes. The problem seems to be: What radiation protection guidance should be applied? A clear and unified policy relating to the application of radiation protection guidance to Plowshare needs to be established.

The development of nuclear energy programs was accompanied by effective radiation safety programs. An exceptionally good radiation safety record resulted. The constructive application of nuclear energy to Plowshare programs should be accomplished with a similar radiation safety performance record. Well-balanced plans to assure radiation safety for all Plowshare programs are a necessity.

As with any safety program, the commonly undiscussed balance between the benefits to be gained and the risks to be incurred needs to be made so that the appropriate radiation protection guidance can be used. The difficult questions for selecting radiation protection guidance for Plowshare are: Who will make the benefits versus risks balance? And then once made, who will accept the balance? It is too much to anticipate a balance that will be accepted by everyone. What, then is the reasonable course of action?

It would appear that only professional authoritative groups, such as the NCRP, FRC, or the ICRP, are in a position adequately divorced from the controls and influences of government, trade unions, and the public to provide the necessary benefit-risk balance, and hence, the selection of the appropriate radiation protection guidance. To provide guidance is not to be confused with determining performance. The AEC and the Public Health Service both have major roles in assessing and evaluating environmental conditions resulting from Plowshare activities. They both have the important role of determining just how well Plowshare programs meet the prescribed radiation protection guidance.

DISCUSSIONS

Presently available radiation protection guides include the publications of the NCRP, ICRP, FRC and the IAEA. All of these recommendations are based on limiting and controlling the radiation dose to the individual, be he a radiation worker or a member of the general public. All concentration limits that are derived are ultimately based on controlling radionuclide intake and depositions so as not to exceed some prescribed dose limit.

One or more of the NCRP or FRC guides may be translated into recommendations for Plowshare radiation protection guidance. For example, some may suggest the prescribed guides for the public exposee or for the general public can yield recommendations directly applicable to Plowshare radiation protection. Others may advocate the use of the dose limits for the radiation workers as Plowshare control limits. A few may advocate dose limits even higher than the annual limits recommended for radiation workers because of the relatively short durations of the Plowshare radiation exposures. I would suggest that only the guidance for the public exposee and for the general public can be unequivocably identified as applicable for Plowshare radiation protection guidance.

Several factors need to be considered in selecting the proper radiation protection guidance for Plowshare. The principal factors of concern are the size of the group to be exposed by a Plowshare program and the extent to which the group can be monitored and moved to control its exposure. These factors may not always be the same for each Plowshare program. This is perhaps the most troublesome and often least appreciated aspect of some current deliberations on this subject. By accepting the concept of different guidance for different Plowshare programs, the risk versus benefit balance can be made more justly. Before developing the potential of this approach, a short review of the basis for the various radiation protection guidance for the workers, the public exposee, and the general public may be helpful.

For the radiation worker, dose limits were established such that a lifetime of occupational exposure within the dose limits would not result in deleterious effects that would be objectionable to the individual or to his physician. The public exposee is identified as the maximumly exposed individual of the general public. His exposure is limited to 0.5 rems per year primarily to avoid exposure of the fetus, although his general state of health and age are important factors also. For the general public, the radiation dose guidance is based on genetic mutation considerations.

Guidance for the occupational exposure to radiation is given by the Equation, Dose = 5(N-18), where the dose is in rems and N is the age of the individual. This expression determines the acceptable occupational dose that may be delivered in a well distributed pattern of both low dose and low dose rate to the whole body. The critical organs, in determining the whole body limit, are the gonads and the red bone marrow. It is important to remember that the pattern of exposure needs to be relatively uniform with no short periods of high exposure followed by long periods of little or no exposure.

The exposure controls for the non-radiation worker are defined in two ways. The public exposee, or individual, should have his radiation exposure limited to 0.5 rems per year; however, the general public as a whole should receive exposure at a rate not exceeding 5 rems in 30 years, or about 0.17 rems per year. The rate of accumulation of this exposure should be relatively uniform. It would not be a good practice to exceed the 0.17 rems/yr rate.

A more detailed review of these dose limits indicate that there are three categories of occupational limits: 1) the critical organ, 2) the limiting organ, and 3) definable special cases. The 5(N-18) dose guidance is applied to the critical organs. A dose of 15 rems per year is defined as the maximum permissible for the limiting organs. Special definable cases are treated individually. Two cases of common interest are potentially pregnant women, whose dose is to be limited to 0.5 rem per year, and the fingers of the hands and the forearm. The fingers may receive up to 75 rems per year; while the transition area, the forearm, is permitted up to 30 rems per year.

Now, to return to the concept of different guidance for different Plowshare programs. If a small group of individuals will be involved in a Plowshare program and if this group can be totally monitored and their dose controlled by actions taken after the Plowshare event, should this become necessary, then control of exposures to near the public exposee limit of

0.5 rems per year seems appropriate. By individual monitoring, their actual radiation exposure from all sources is known. If a large group of individuals will be involved, such that individual monitoring or subsequent control is not feasible or possible for any reason, then the general public guidance should be used and their exposure should be limited to 5 rems per 30 years, or about 0.17 rems per year.

Some may advance the concept that the short duration of the exposure for Plowshare detonations provides increased latitude and tends to permit higher doses than those normally recommended for the general public. Such an approach is not to be recommended because even short-term radiation levels, equal to or approaching those established as acceptable for radiation workers, may not be without some deleterious effect to special groups within the general population, particularly those in early pregnancy.

The very wide variations between the makeup of a worker population and a general population support the appropriateness of the public exposee or the general public limit guidance. Not many would advocate the exposure of pregnant women, children, the elderly, sick or chronically ill to doses comparable to those permitted safely to a select group of radiation workers or to a group whose exposure was monitored and was controllable to a reasonable extent.

The ability to monitor and control the radiation dose to the population involved should be realistically determined to decide if the public exposee or the general population guidance should be used. The radionuclides to be encountered and their exposure path to and in the body should be determined so that the allowable dose for each radionuclide can be established. The environmental pathways and dietary habits of the population can be used to determine the permissible rates of intake for each radionuclide. Dilution factors and radiation control practices appropriate to the specific needs of the Plowshare program can be defined--all within the radiation protection guidance currently available. One really needs to practice the old cliche, "Expect the Unexpected," in each step of this calculation.

What about considerations arising from possible multiple sources of exposure? Others have recommended reduction factors for the general population limits of 10 or 100 to 0.5 rems per year or 0.005 rems per year in the assignment of acceptable dose accumulation rates to particlular radionuclides to make allowance for multiple radiation source contributions. Let's think about such calculations. They do not affect the basic dose guidance for Plowshare. They are a type of "allowance factor" to be applied in calculating doses to be permitted from particular radioisotopes. If, for a given Plowshare program, three radionuclides were present for ingestion and each of these had the whole body as the critical organ, then allowing 1/3 of 0.5 rems per year or 1/3 of 0.17 rems per year for each radionuclide would be in order, however, the basic guidance has not changed. If some other unrelated source of exposure could be identified, then an appropriate allowance also should be made for it. However, a practical analysis of the recommendations to use reduction factors of 10 or 100 arbitrarily for all Plowshare programs immediately runs into difficulty. While keeping radiation exposure at the lowest practical level is our prime and absolute objective, it is, however, not appropriate to prescribe mandatory control limits with unneeded conservatism. One should consider multiple radiation sources exposures of the general public only as they become identified. It is not necessary to develop Plowshare protection guidance from such a restrictive position.

One can always consider the likelihood that a Plowshare population will also be in a position to receive substantial multiple source exposures from unknown activities. With the limited current Plowshare program and the diverse locations where future programs may be conducted, the potential for exceeding the population control limits from multiple sources exposures unknowingly seems remote. To impose the more restrictive controls at this time is to apply an unjust, improper benefit-risk burden on the developing Plowshare program.

Guidance at 5 rems per 30 years or less also seems advisable when considering the use of Plowshare products by the general public. Consider the tritium contamination in Plowshare-assisted natural gas wells. The distribution of this natural gas and its small amount of tritium to homes over very wide parts of the country can lead to the exposure of a very large population under unmonitored conditions. This is clearly a general population exposure in its fullest sense.

One might consider the benefit-risk balance made by a family with respect to natural gas associated with Plowshare programs. I dare speculate that many a family would make the benefit-risk balance at a higher cost of gas and the absence or near-absence of tritium. Similar considerations enforce and support actions to very seriously keep radiation exposures as low as practical. There is more in the benefit-risk balance than company profits and technical safety. Each family will have its own criteria for measuring benefits and risks and hence, the general acceptability of Plowshare-linked products. One should be reluctant to break with the long standing guidance on exposure of the general population in any Plowshare program. It would seem prudent to advise exposure control limits no more restrictive and no more liberal than those used for some time now. Any change would call for a complete review of the technical basis for change by the NCRP or FRC.

We cannot arbitrarily decide what cost will be attributed to Plowshare radiation protection activities due to the selected radiation protection guidance or what cost can be devoted to ecological studies to support dose estimations. Each situation may be unique, and adequate information needs to be collected before, during and after each program to demonstrate that a completely safe program within the dose guidance is attained. The conditions of each Plowshare program will determine the cost required to provide total adequate, but not excessive, radiation protection.

Two questions of thoughtful concern: What are the international legal aspects of programs on foreign soils? What recourse might occur if improper programs were planned or actually performed? The treaties authorizing U.S. Plowshare programs on foreign soils will undoubtedly determine the levels of exposure that will be anticipated.

Some international authoritative review body would seem to have a role to play in providing assurances that necessary and adequate precautions and care were taken in planning and executing each test. Perhaps an arm of the IAEA could provide this help. It will be a challenging task. It needs to be performed soundly, but on a very timely basis. An overseer--not a roadblock--is needed.

SUMMARY

It appears appropriate to evaluate each Plowshare program individually, providing the necessary studies and population considerations, so that one may use the correct dose limit guidance for determining acceptable conditions. The AEC and the Public Health Service need to give careful attention to collecting and analyzing environmental exposures and dose data so that we may learn from experiences and assure safe conditions. We need to maintain the good record of the nuclear energy program by not making unsafe errors in estimating the consequences of any Plowsare programs.

Plowshare can be performed safely. To do so requires good judgment, sound application of existing radiation protection guidance, and sufficient funding to meet the needs of practical safety programs. A safe approach using the public exposee or the general population dose control limits, as the situation may demand, is necessary to help\assure the rapid development of Plowshare programs. A high priority should be assigned to developing methods to apply the existing radiation protection guidance so that Plowshare programs may proceed safely.

There seems to be no doubt but that the peaceful applications of nuclear energy in Plowshare programs will develop as rapidly as funding and commercial opportunities present themselves. The safe history of the nuclear industry, the long-term potential benefits, and the varied applications for developing Plowshare technology may be at stake if authoritative and sound radiation protection methods are not incorporated in all Plowshare applications. If Plowshare does not get off with a safe, well accepted record of radiation management and control, then its potential benefits will be doubly difficult to develop. It would be a long and difficult task for Plowshare to attain a right finish after making a wrong start.

QUESTION FOR HERBERT M. PARKER

1. From R. Duff:

Will you comment more quantitatively about the non-linear effects of low level radiation exposure recently discovered?

ANSWER:

Most radiation protectionists are generalists who have some competence in reviewing the work of others. It has taken three decades, remember, to get some sense into this despite the fact that the very best radiobiologists in the world have been working on it. I think it would be very imprudent of me to comment at great lengths. I would refer the questioner to the genetic case which is the one, I think that socially is the most troublesome. I say that partly on the grounds that it's not too bad if we louse up this generation, but if we louse up the next hundred generations, that's a different issue. Work in the area of genetics is essentially done through the outstanding findings of Russell and Russell at Oak Ridge. Those of you who were at the other symposium I addressed about a month ago heard a superb review by Dr. Russell in terms that those of us who are not geneticists, like myself, could really understand and I believe that is going to be published by Lawrence Radiation Laboratory. I wouldn't know a finer quick reference to what really has been found out about effects of low dose rate and low dosage both, in this case of course in the mouse and carried over inferentially to the human case. Male and female cases are very different and there may be some experts in the room who would volunteer to fill this in more fully. I would rather not.

SESSION V - EXISTING AND REQUIRED RESEARCH FOR DEVELOPMENT OF RADIATION PROTECTION GUIDANCE FOR PLOWSHARE

Chairman: Mr. Charles L. Weaver
Bureau of Radiological Health
U. S. Public Health Service
Rockville

METHODS OF ESTIMATING POPULATION EXPOSURES FROM PLOWSHARE APPLICATIONS*

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ABSTRACT

When estimating doses to populations it is necessary to divide the total population into groups that have parameters of similar type and magnitude in order to identify critical population groups. Age groups constitute the most basic and generally useful way of dividing the total population for estimating dose. Models for estimating dose, particularly the internal dose from inhalation and ingestion of radioactivity, should be written as a function of age. The importance of considering age-dependency is emphasized by the fact that some of the internal dose parameters change by as much as a factor of ten for some radionuclides when comparing a one year old with an adult. A computer code called INREM has been written which can consider all internal dose parameters as a function of age. The major limitation in using this computer code for all radionuclides is the paucity of age-dependent input data for many radionuclides. Tritium, iodine, cesium, and strontium nave been studied in detail with INREM and the results and interpretations are discussed. Another code, EXREM, computes the external dose rates and cumulative doses from both beta particles and gamma photons from submersion in a radioactive cloud, submersion in contaminated water and exposure above a contaminated land surface. This code can consider up to 25 Plowshare detonations and a variety of combinations for calculating doses and dose rates in relation to a detonation schedule. The importance of using both INREM and EXREM to estimate the total dose to a population group is stressed.

INTRODUCTION

Not many years ago almost all estimates of internal radiation dose were based on biological parameters developed for a notional

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*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

adult radiation worker known as "standard man." The standard man concept has been useful for estimating radiation dose to the adult radiation worker. When this concept is applied to the general population, the dose estimates are inadequate because standard man represents only a relatively small group in the general population. Most health physicists recognize this shortcoming and considerable effort has been expended to develop methods for estimating potential doses to other groups in the population. Additional effort is justified here because potential sources of radiation exposures to the general population are increasing at a rapid rate. We do not mean to imply that every source of potential exposure represents a real hazard to man. Everyone knows that the atomic energy industry has an excellent record of safety both for the worker and for the public. The point which we wish to make here is that, in order to maintain this outstanding safety record, the expertise for estimating exposures to the general population must keep pace with expanded uses of atomic energy. In the past few years we have seen a phenomenal growth in nuclear power generation, and possibly in the near future we will see a beginning of the utilization of the Plowshare concepts. Thus, emphasis should be placed now on further development of methods for estimating the expected doses to various groups comprising the general population.

Objectives for Estimating Dose

Not all situations require estimation of expected dose; sometimes an upper limit or conservative estimate of dose is adequate. One of the most important objectives of a program for estimating potential radiation doses from a Plowshare application is to provide evidence of compliance with regulations and guidelines safeguarding the public health. Some of the recognized authorities publishing guidelines and regulations on radiation exposure limitations include the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), the Federal Radiation Council (FRC), U. S. Atomic Energy Commission (AEC), and the state regulatory agencies. One of the hoped for achievements of the Plowshare sponsored research at ORNL is that present efforts to predict expected doses from various Plowshare applications will be successful in providing some of the necessary ground work for the FRC and AEC regulatory groups to set guidelines applicable in this area. Presently, there are no specific guidelines or regulations dealing with the possible population exposures from Plowshare applications.

The preliminary predetonation safety of the operation can be evaluated usually with conservative methods such as those recommended by Ng _et al_. of the Lawrence Radiation Laboratory.[1] The technique which they have adopted for predicting the maximum radiation dose to man from internal sources is based upon the specific activity concept. The conservative aspects of this approach were analyzed in detail by Kaye and Nelson,[2] as were the many factors which could affect the usefulness of this approach for assessing the possible radiological consequences of activity releases. The limitations appear to be most restrictive for terrestrial environments where there may be incomplete mixing and unequal availability of the radioisotope and its stable analogue.

Ng and co-workers have emphasized that the preshot prediction should not serve the sole purpose of preshot rad-safe analysis, but it should also provide guidance for the post-shot documentation. They point out that this guidance may include where to measure, what to measure, and even the precision required for the measurements. Since the post-detonation analysis is based on actual measurements, it can be expected to yield results which will be useful for improving the predetonation predictions of safety.

We believe that there is a distinct possibility that the future of Plowshare applications may be influenced more by public acceptance than by any other important factor. Proposed operations may meet all of the requirements of the recognized authorities that have pertinent regulations and guidelines, but the public may not want to be subjected to any radiation dose resulting from a Plowshare application. We believe that public opinion will exert a strong enough influence to require very detailed hazard analyses which estimate the expected dose to each population group exposed by any peaceful application of nuclear explosives.

Each new application may be expected to benefit from the lessons learned from previous applications. Eventually, this feedback should result in an accumulation of data necessary to make good dose predictions.

Essential Information for Dose Estimates

The information required for a program to estimate dose to members of the general public has been divided arbitrarily into five categories by Kaye et al.[3] for activity releases to the environment. The five categories of information are: 1) inventory of radionuclides produced and fractions released to the environment; 2) environmental dilution or concentration factors; 3) intake and/or exposure-time factors; 4) biological parameters and habits characterizing the populations being exposed; and 5) dose-estimation equations. The extent of this information indicates the complexity of dose estimation for the general public. A successful program requires the cooperation of many individuals and groups and careful integration of the essential information to provide maximum effectiveness in protecting public health.

Modes of Exposure and Exposure Pathways

A "mode of exposure" is the manner in which a person is exposed. The principal modes of exposure expected to be responsible for most, if not all, of the potential exposures from peaceful nuclear detonations are represented schematically in Figure 1. The modes of external exposure are submersion in a radioactive cloud, exposure above a contaminated landscape, and submersion in contaminated water. The modes of internal exposure are inhalation and ingestion of radioactivity. For external exposure, the radiation source is exterior to the body of the person being irradiated; and when either the person or the source is removed, the person ceases to be exposed. Internal exposure is a different case because the radiation source is inside the body of the person, and the exposure may continue for years after the last intake of radioactivity, if the effective half-time of the radionuclide in the body is sufficiently long.

Exposure pathways are the actual routes of exposure for a particular mode. Consider the ingestion mode; the pathways for this mode are the different intakes of contaminated foods and beverages. Submersion in water would probably be made up of two pathways, bathing and swimming.

The modes of exposure (and the exposure pathways making up these modes of exposure) which will result in the largest dose equivalents to the population groups depend upon many factors. Of primary importance is the type of nuclear application, i.e., gas stimulation, ore fracturing, underground cavity formation, or cratering for a canal or harbor. Many applications will have to be evaluated separately before generalizations can be formulated regarding the importance of the various modes and pathways of exposure.

Ecological Systems Analysis as a Method for Predicting the Expected Dose

Although systems analysis is a relatively new technique to the field of ecology, it has been used successfully for a number of years in many other areas of science, engineering, and business. In this respect, we define systems analysis as the study of the dynamic behavior of a system of coupled compartments. The major question to be answered with the systems analysis methodology is, "How much of the radioactivity released to the environment will expose man both internally and externally as a function of time?"

We visualize the coupling of compartments as routes for the transfer of materials between compartments making up the system. This may be represented graphically by a coupled compartment diagram, and differential or difference equations may be written for the inventory of materials in each compartment. Because of the interconnections, or coupling of compartments, no one compartment functions on its own; the dynamic behavior of each compartment is determined by the net effect of all of the other compartments. Thus, it is necessary to use a computer to solve the equations to determine the temporal responses of all of the compartments making up a system. An example of a familiar system for health physicists is a pasture contaminated by fallout containing radioiodine. The gross compartments of interest in this system include soil, runoff, forage, cattle, beef, and dairy products.

To utilize the systems analysis approach for assessing the expected dose from an environmental release, the following three steps are involved: 1) environmental measurements and experimentation, 2) parameter identification, and 3) systems analysis. The ecological research must be carefully planned and carried out to measure the environmental transfer coefficients which quantify the inter-compartmental transfers. The environmental transfer coefficients of a system are the most important and unique parameters required for systems analysis. The second step, parameter identification, is applied to the field data which are plotted as a function of time. Parameter identification is the actual assignment of a numerical value to the coefficient based on experimental data. Problems of uniqueness and time-varying parameters are encountered here, but considerable help is available from techniques available in other fields. Steps 2 and 3 are independent of the type of data (biological or physical) because these steps are mathematical and, as stated above, have already been highly refined by work in other fields. Many excellent systems analysis computer codes have already been written and may be used without major change for environmental hazards analysis. For instance, the MATEXP and SFR-3 systems analysis codes written for nuclear reactor dynamics studies were used by Kaye and Ball[4] in the systems analysis of a coupled compartment model for radionuclide transfer in a tropical environment. The MATEXP code utilizes a transient analysis while the SFR-3 utilizes a frequency response and a sensitivity analysis which relates parameter uncertainties to performance uncertainties. Sensitivity analysis has great promise for identifying critical pathways and critical population groups. If we let ΔR_i represent the response of a compartment of interest (change in concentration of radioactivity in a potential food item) to ΔP_j, a change in a parameter (the environmental transfer coefficient is increased or decreased), then we can define sensitivity mathematically as

$$\mathrm{Lim}_{\Delta P \to 0} \frac{\Delta R_i}{\Delta P_j} = \frac{\partial R_i}{\partial P_j} . \qquad (1)$$

This relationship can be used to indicate which parameters are most accountable for the radioactivity in a particular food item and thus may suggest some remedial action to divert this radioactivity to a compartment which has negligible inputs to man. Complex environmental systems which have multiple couplings with feedbacks are readily adapted to systems analysis if the transfer coefficients are known. Environmental transfer coefficients are not easy to determine and the need for them has not always been apparent. However, information on a few systems is already available in the literature to formulate environmental transfer coefficients which can be used in working models. Radioecological research underway at Oak Ridge National Laboratory is producing a body of information on radionuclide cycling which is useful for systems analysis.

Considerable emphasis is being placed on systems analysis as a major technique in proposals supporting the International Biological Program (IBP). It may be that IBP will result in the first large scale test of environmental systems analysis, and thus lay the groundwork for more extensive applications in environmental dose estimation.

DEVELOPMENT OF AGE-DEPENDENT MODELS FOR INTERNAL DOSE

To identify the critical population groups, it is necessary, when estimating doses to populations, to consider the total population in terms of homogeneous groups having parameters of similar type and magnitude. Age groups constitute a basic and generally useful way of dividing the total population for estimating dose. Models for estimating dose, particularly the internal dose from inhalation and ingestion of radioactivity, should be written as a function of age. The importance of considering age-dependency is emphasized by the fact that certain of the internal dose parameters change by as much as a factor of ten for some radionuclides when comparing a one year old with an adult. If the exposure continues over a long enough period, the aging of the person becomes a factor, i.e., the biological parameters and the intake function may change, and the internal dose computations should be made using the applicable input data.

Guidance is given in ICRP Report 2 for developing equations for estimating internal dose to the various organs of standard man resulting from ingestion and inhalation of radioactivity.[5] These basic ideas can be used for developing a model which has each term expressed as a function of the age of the individual. Such a model can be used to compute the dose as a function of age, which may be useful in identifying the critical population groups as recommended by the ICRP in Report 7.[6]

All Organs Except the GI Tract

The rate of change of organ burden B is given by

$$\frac{dB}{dt} = If - \lambda B \ (\mu Ci/day), \tag{2}$$

where I = daily intake (μCi/day),

f = fraction of I deposited in the organ, and

λ = effective elimination constant (day^{-1}).

This expression is a modification of Eq. (5) of ICRP Report 2, and may be expanded to apply to the i^{th} radionuclide in the k^{th} organ for a person born at t_b. The age of the individual at time t (usually t = 0 at the time of detonation) is $t - t_b$ and leads to the following revision of Eq. 1 which is rearranged for solution as a non-homogeneous, first order, linear differential equation:

$$\frac{dB_{ik}}{dt} + \lambda_{ik}\,(t - t_b)\,B_{ik} = I_i\,(t - t_b,\, t)\,f_{ik}\,(t - t_b)\ (\mu Ci/day). \quad (3)$$

Note that I is written as a function of age, $t - t_b$, and as a function of time, t. This equation is now of the form

$$B' + a(t)\,B = b(t),$$

where $a = \lambda_{ik}\,(t - t_b)$ which we let equal $\lambda_{ik}(r)$, and

$$b(t) = b(s) = I_i\,(s - t_b,\, s)\,f_{ik}\,(s - t_b).$$

In this formulation, both s and r are dummy variables. It follows that the solution to Eq. (3) for organ burden is given by

$$B_{ik} = \exp\left[-\int_{-t_b}^{t-t_b} \lambda_{ik}\,(r)\,dr\right] \int_o^t I_i\,(s-t_b,\, s)\,f_{ik}(s-t_b)$$
$$\exp\left[\int_{-t_b}^{t-t_b} \lambda_{ik}\,(r)\,dr\right]\,ds\ (\mu Ci) \quad (4)$$

The dose rate dD_{ik}/dt is simply the product of organ burden, times the effective absorbed energy per gram $[\varepsilon_{ik}(t-t_b)/m_k(t-t_b)]$ of critical organ, times a constant to convert MeV to rems, and is written

$$\frac{dD_{ik}}{dt} = \frac{51\ B_{ik}\,(t-t_b,\, t)\ \varepsilon_{ik}(t-t_b)}{m_k(t-t_b)}\ (rem/day) \quad (5)$$

The next step is to write the integral form of the equation by substituting the right side of Eq. (4) for $B_{ik}(t-t_b,\, t)$ in Eq. (5), and changing the sequence of integration so that we integrate first with respect to t as written here:

$$D_{ik}(t_1,\ t_2,\ t_b) = 51\int_{t_1}^{t_2} \{I_i\ (s-t_b,\ s)\ f_{ik}(s-t_b)\ \exp\left[\int_{-t_b}^{s-t_b} \lambda_{ik}(r)\ dr\right]$$

$$\int_{s}^{t} \frac{\varepsilon_{ik}(t-t_b)}{m_k(t-t_b)} \exp\left[-\int_{-t_b}^{t-t_b} \lambda_{ik}\ (r)dr\right]\ dt\}\ ds + 51\int_{o}^{t_1} \{I_i(s-t_b,s)$$

$$f_{ik}(s-t_b)\ \exp\left[\int_{-t_b}^{s-t_b} \lambda_{ik}(r)dr\right]\int_{t_1}^{t_2} \frac{\varepsilon_{ik}(t-t_b)}{m_k(t-t_b)}$$

$$\exp\left[-\int_{-t_b}^{t-t_b} \lambda_{ik}(r)\ dr\right]\ dt\}\ ds \quad (rem). \tag{6}$$

The limits of integration have been changed to account for the change in sequence of integration. It is implicit that for $t < t_1$, I_i and ε_{ik} are equal to zero. Both t and s in Eq. (6) are dummy variables and they may be interchanged to obtain the final form which applies to any organ except the GI tract:

$$D_{ik}(t_1,\ t_2,\ t_b) = 51\int_{t_1}^{t_2} \{I_i(t-t_b,\ t)\ f_{ik}(t-t_b)\int_{t}^{t_2} \frac{\varepsilon_{ik}(s-t_b)}{m_k(s-t_b)}$$

$$\exp\left[-\int_{t-t_b}^{s-t_b} \lambda_{ik}(r)dr\right]\ ds\ \}\ dt \quad (rem). \tag{7}$$

Equation (7) above is the model which is programmed in the INREM code for cumulative dose to all organs except the GI tract.

The relationships of the time variables used in Eq. (7) are illustrated with the following time scale:

The reference point (t_0) is usually set equal to the time of the first detonation for convenience. All other points in time are evaluated by their position relative to t_0. The time of birth (t_b) of the individual need not occur before t_0 as shown here; it may take on any value equal to or less than t_1. The beginning and the end of the time period for which dose is to be integrated are designated t_1 and t_2, respectively. Radioactivity entering the body prior to t_1 is not included in the dose calculation; therefore, t_1 usually is set equal to the time at which radionuclide intake begins. The variables t, s, and r are dummy variables of integration for the three integrals in the equation.

This model implies a continuous intake changing with age and time, and all other terms changing with age. Since the hand solution of Eq.(7) is not practical, it is in a computer code called INREM. Great flexibility is built into the code so that many radionuclides, body organs, and age groups can be handled in one run of the computer. The code handles standard-man calculations as well as age-dependent calculations.[7,8]

The radionuclide intake (μCi/day) is one of the primary input data required for an age-dependent calculation. This information is put into INREM as "points" from a graph of μCi/day intake vs. time since the reference detonation. There is one graph per age group and the number of points taken from each graph is usually determined by the number of inflections in the curve, since the computer actually reconstructs the graph by a linear interpolation between points. INREM accepts up to 100 such intake points per age group and up to 25 age groups.

GI Tract as the Critical Organ

For dosimetry purposes, the ICRP Report 2 recognizes the GI Tract as being divided into four segments (stomach, small intestine, upper large intestine, and lower large intestine). This requires that a different equation be written to estimate the dose to each segment as a result of the passage of radioactivity. Such equations must include the time required for the intake to reach the segment of interest, the time required for emptying the segment, the mass of the segment plus contents, and the fraction of the ingested radioactivity which is absorbed by the blood. An alternative way of estimating the dose to the GI tract from any intake is to relate the intake to dose received from intake at the $(MPC)_a$ or $(MPC)_w$. The advantages of this approach are that only one equation is required and that it utilizes the MPC for the critical segment which already has built into it all the factors mentioned above.

If the maximum permissible dose rate is 0.3 rem/wk, then we can write

$$\frac{0.3/7}{A_j\ (MPC)_{ij\alpha}} = \frac{rem}{\mu Ci} \tag{8}$$

where A_j = intake (cm^3/day) of air (j=1) or water (j=2), and
$(MPC)_{ij\alpha}$ = the maximum permissible concentration ($\mu Ci/cm^3$) of the i^{th} radionuclide in air (j=1) or water (j=2) where the i^{th} radionuclide is soluble (α=1) or insoluble (α=2).

The dose from any single intake can be computed by direct substitution into Eq.(8) and by assuming that the simple proportion holds. Rewriting Eq.(8) by substituting the single µCi intake, S_i, for µCi in the denominator gives

$$D_{ij\alpha} = \frac{0.3/7\ S_i}{A_j (MPC)_{ij\alpha}}\ (\text{rem}). \tag{9}$$

This equation applies to standard man only, and must be multiplied by a modifying factor, h (ℓ), to make it age dependent. The dose to a person in the ℓth age group is given by

$$D_{ij\alpha}(\ell) = \frac{0.3/7\ S_i h(\ell)}{A_{jn} (MPC)_{ij\alpha}}\ (\text{rem}) \tag{10}$$

for a single intake. The subscript n is an index for standard man. As written in Eq.(10), h(ℓ) is the product of three modifying internal dose variables found in Eq.(14) of ICRP Report 2, and which are ratioed to their respective standard man values. Other variables, such as residence time of food in the critical segment could be included also, but no body of age-dependent data is available for these parameters. Thus,

$$h(\ell) = m_n/m_\ell \cdot \varepsilon_{i\ell\alpha}/\varepsilon_{in\alpha} \cdot f_{i\ell j\alpha}/f_{inj\alpha}\ , \tag{11}$$

where m_ℓ = mass (g) of the critical segment of the GI tract of an individual in the ℓth age group,

$\varepsilon_{i\ell\alpha}$ = effective absorbed energy (MeV) of the ith radionuclide of type α in the critical segment of the GI tract of an individual in the ℓth age group, and

$f_{i\ell j\alpha}$ = fraction of the intake from inhalation or ingestion of the ith radionuclide of type α reaching the critical segment of the GI tract of an individual in the ℓth age group.

As a matter of convenience for simplifying the final form of the model, let

$$P_k(t-t_b) = m_n/m_\ell\ ,$$

$$Q_{i\alpha}(t-t_b) = \varepsilon_{i\ell\alpha}/\varepsilon_{in\alpha},\ \text{and}$$

$$R_{ij\alpha}(t-t_b) = f_{i\ell j\alpha}/f_{inj\alpha}, \tag{12}$$

where $t-t_b$ is the age of the individual in relation to the reference time as defined for the model for all organs except the GI tract.

If we assume a continuous intake of I_i μCi/day as a function of age and time, the *cumulative dose model can* be written in the integral form after substitution of the age-dependent correction factors for h(ℓ):

$$D_{ij\alpha}(t_1,t_2,t_b) = \frac{0.3/7}{A_{jn}(MPC)_{ij\alpha}} \int_{t_1}^{t_2} I_i(t-t_b,t)\ P_k(t-t_b)\ Q_{i\alpha}(t-t_b)\ R_{ij\alpha}(t-t_b)dt \quad (13)$$

Equation (13) is programmed in the INREM code for calculating cumulative dose to the GI tract.

Genetic Dose

Genetic dose is considered at the level of the individual and at the population level because separate radiation safety guidelines are available for each.[9] The *genetic dose to an individual* is determined on the basis of the dose estimates provided by the INREM and EXREM codes, supplemented with any additional information which will improve the assessment of the expected gonad dose. At the population level, genetically significant dose is the factor requiring evaluation. Genetically significant dose is *defined in the 1958 Report of* UNSCEAR[10] as the dose which, if received by every member of the population, would be expected to produce the same total genetic injury to the population as do the actual doses received by the various individuals. Estimates of genetic doses to individuals are used in conjunction with demographic information to evaluate the *genetically significant dose to the population.* The formulation used for that purpose is adapted from the 1958 Report of UNSCEAR. The genetically significant dose is given by

$$D^* = \frac{1}{wN} \sum_k d_k^* N_k^* w_k^* \quad (rem) \qquad (14)$$

where

$*$ denotes the sex,

k denotes the age group,

D = genetically significant dose (rem),

w = future number of children expected by an average individual,

N = total number of *individuals in the population,* and

d = gonad dose (rem) of an individual.

DEVELOPMENT OF MODELS FOR EXTERNAL DOSE

In considering external exposures, one must first decide on the precision required so that appropriate *models can* be developed. Some of the factors that may be given consideration are concentration gradients, terrain roughness, shielding, build-up, distances from contaminated surfaces and volumes, and cloud direction and speed. Each of these factors may be expected to affect the dose rate at the location of interest, and each should be considered for a detailed calculation where the source, geometry, and environmental factors are well defined. This detailed approach is not practical in a general assessment of external exposure from a large number of nuclides at many locations over thousands of square miles.

We have developed a computer code called EXREM which computes doses and dose rates for the three modes of external exposure mentioned earlier--exposure above a contaminated surface, submersion in contaminated air, and submersion in contaminated water. This code is tailored to our present requirements, but can be modified easily as the requirements change. Since some proposed Plowshare projects require multiple detonations, the EXREM code is able to handle up to 25 consecutive detonations and perform the necessary bookkeeping for build-up and decay of up to 200 parent and daughter nuclides starting at the time of the first detonation and continuing to any time of interest. The models programmed for submersion in air and water are the adiabatic type; that is, the contaminated medium is assumed to be infinite in extent and of uniform concentration. When this is not the condition, the dose estimates will be proportionately conservative.

The total external dose equivalent (rems) from beta particles ($q=\beta$) or gamma photons ($q=\gamma$) of the i^{th} radionuclide at the ℓ^{th} location accumulated from exposure from t_1 to t_2 for the q^{th} mode of exposure is denoted by

$$TD_{ipq\ell}(t_1,t_2) = D_{ipq}\int_{t_1}^{t_2} C_{ip\ell}(t)dt \qquad (15)$$

where i = radionuclide index,

q = radiation index(β for beta radiation; γ for gamma radiation),

p = exposure mode index (w for water; a for air; s for surface),

ℓ = location index,

t_1 = time (hours) for beginning of exposure,

t_2 = time (hours) for ending of exposure,

D_{iqp} = dose-rate factor $[(\frac{rem \cdot cm^3}{\mu Ci \cdot hr})$ for p=w and p=a; $(\frac{rem \cdot cm^2}{\mu Ci \cdot hr})$for p=s], and

$C_{ip\ell}(t)$ = concentration $[(\mu Ci/cm^3)$ for p=w and p=a; $(\mu Ci/cm^2)$ for p=s] at time t.

The EXREM code calculates D_{iqp} separately for both β and γ- radiation from a model appropriate for the mode of exposure p using input data for radionuclide i. The models used in this code for the various modes of D_{iqp} have been described previously.[8,11]

The concentration, $C_{ip\ell}(t)$, is derived from the nuclide chain equations for radioactive decay. For a single environmental release, an explicit expression for the concentration at time t of the i^{th} radionuclide in a pathway is denoted by

$$C_{ip\ell}(t) = \begin{cases} C^{o}_{ip\ell}\exp(-\lambda_1 T), & i=1, \\ C^{o}_{ip\ell}\exp(-\lambda_i T)+T \displaystyle\sum_{k=1}^{i-1}\left[C^{o}_{kp\ell}\sum_{j=k}^{i-1} Y_{ij}(T)\lambda_{j+1}f_j \prod_{\substack{\ell=k \\ \ell\neq j}}^{i-1}\left(\frac{\lambda_{\ell+1}f_\ell}{\lambda_\ell-\lambda_j}\right)\right], & i>1, \end{cases} \quad (16)$$

where

$$T = t-t_0 ,$$

$$\prod_{\substack{\ell=k \\ \ell\neq j}}^{i-1}\left(\frac{\lambda_{\ell+1}f_\ell}{\lambda_\ell-\lambda_j}\right) = 1 \quad \text{if } k=i-1 ,$$

$$Y_{ij}(T) = \left[\frac{\exp(-\lambda_j T) - \exp(-\lambda_i T)}{(\lambda_i-\lambda_j)T}\right] ,$$

λ_i = radiological decay constant (hours^{-1}) of the i^{th} radionuclide,

f_i = fraction of nuclei of the i^{th} radionuclide which decays to the $i+1^{st}$ nuclide in the pathway,

t_0 = time (hours) of environmental release,

$C^{o}_{ip\ell} = g_{pi\ell}Y_i$,

$g_{pi\ell}$ = location correction factor for the i^{th} radionuclide, the p^{th} mode of exposure, and the ℓ^{th} location, and

Y_i = yield (μCi) of the environmental release.

To determine the concentration of a radionuclide in a chain containing more than one pathway, contributions for the nuclide are summed for each pathway which is unique up to that radionuclide.

The concentration, ${}_{M}C_{ip\ell}(t)$, at time t of the i^{th} radionuclide resulting from M environmental releases is obtained by evaluating Eq.(16) where

$$C^{o}_{ip\ell} = {}_{M-1}C_{ip\ell}(\tau_M) + g_{pi\ell M}Y_{iM} , \quad (17)$$

and where

τ_M = time (hours) of the M^{th} environmental release,

$T = t-\tau_M$,

$g_{pi\ell M} = g_{pi\ell}$ for the M^{th} environmental release,

$Y_{iM} = Y_i$ for the M^{th} environmental release, and

${}_{M-1}C_{ip\ell}(\tau_M)$ = the concentration at time τ_M of the i^{th} radionuclide resulting from the first M-1 environmental releases.

Obviously, only digital computer solution is practical for the external dose model because the complexity of the calculations involves multiple detonations, decay chains with branching, several modes of exposure, and the large number of radionuclides usually considered. The EXREM code has flexibility in handling problems of varying complexity. Up to fifty dose rates and/or total doses may be computed for each nuclide in each mode of exposure. This code prints out separately the doses and dose rates from the gamma photons and the beta particles of each radionuclide, as well as the total dose and total dose rate by summing the beta and gamma contributions (for some assessments, dose rate as well as total dose is important). The latest version of this code is described in more detail in a publication by Turner.[12]

USING EXREM AND INREM TO ESTIMATE DOSE

A simple problem is postulated to apply the methodology discussed in this paper. There are two reasons for including this problem. First, to identify the type of input data required to carry out the computations, and, second, to illustrate the format of the results of the dose computations for a cratering type of Plowshare application.

Many radiological assessments of a contaminating event are based on conservative assumptions. Frequently, life-time or infinite gamma doses are calculated for external exposure with the assumption that the radiation field decreases as a function of time due to radioactive decay only. Actually, this condition represents the upper limit, because environmental factors such as loss of radioactivity to surface waters from erosion, infiltration into the soil profile, wind, removal by animals, plowing, etc., will tend to decrease the radiation field also. Radioactive decay can be viewed as a loss of radioactive atoms from the system, commonly denoted by the radioactive decay constant, λ_r, and the environmental inputs and losses can be described by the algebraic sum of the appropriate transfer coefficients. For simplicity, we consider only the net coefficient here, denoted as the environmental transfer coefficient, λ_e, which leads to the relationship

$$\lambda = \lambda_e + \lambda_r \ , \tag{18}$$

where λ is defined as the effective decay constant. Substituting the corresponding half-times into Eq.(18) gives the following relationship:

$$T = \frac{T_e T_r}{T_e + T_r} , \qquad (19)$$

where

T = effective half-time,

T_e = environmental half-time, and

T_r = radioactive half-life.

In the treatment of the hypothetical problem which follows, we compute both expected doses using $T = T_e T_r / T_e + T_r$ and conservative doses using $T = T_r$ and compare one with the other.

The levels of radioactivity we choose are completely arbitrary and are not related to any real Plowshare applications. Figure 2 is a block diagram representing in abstract form the problem we postulate and analyze in the following pages.

The type of application postulated is a project requiring two cratering detonations which vent to the atmosphere. Only ^{137}Cs and ^{137}Ba are vented, leading to exposure of the population by the modes shown in Figure 2.

Outline of Hypothetical Problem

I. Source Term
   A. Production vented per detonation = 1 Ci ^{137}Cs-^{137}Ba.
   B. Detonation schedule: Det. No. 1 at t=0 and Det. No. 2 at t=30 days.
II. Radioactive Cloud
   A. Time to reach the location of interest = 4 hours.
   B. Time to pass over the location of interest = 1 hour.
   C. Concentration in cloud = $10^6 \mu$Ci x $10^{-14}/\text{cm}^3$ = $10^{-8} \mu\text{Ci/cm}^3$, where $10^{-14}/\text{cm}^3$ is the location correction factor relating the fraction vented and the concentration per cm^3 of air at the location of interest.
   D. Inhaled μCi per detonation by a person in the ℓ^{th} age group = $10^{-8} \mu\text{Ci/cm}^3$ x cm^3 air breathed in 1 hour by that person.[6]
III. Deposition of Fallout on Landscape
   A. Exposure to contaminated landscape.
      1. Concentration = $10^6 \mu$Ci x $10^{-13}/\text{cm}^2$ = $10^{-7} \mu\text{Ci/cm}^2$, where $10^{-13}/\text{cm}^2$ is the location correction factor relating the fraction vented and deposition per cm^2 of land surface at the location of interest.

2. Height above landscape for which dose is to be estimated = 100 cm.

3. Environmental half-time of ^{137}Cs on the land surface = 1 year; thus, the effective half-time of ^{137}Cs on land surface is 0.97 years.

B. Ingestion of food.

1. Age-dependent parameters in the INREM code are evaluated with the information in Tables 1 and 2.

2. Maximum concentration of ^{137}Cs in food after each detonation = $10^{-9}\mu Ci/g$; the maximum is reached on the 14th day following the detonation.

3. Radionuclide intake (μCi/day) = $I' \times C$.

4. Effective half-time of ^{137}Cs in the food is one year.

IV. Transfer of Radioactivity to Surface Waters

A. Submersion in water.

1. Concentration = $10^{6}\mu Ci \times 10^{-13}/cm^{3} = 10^{-7}\mu Ci/cm^{3}$, where $10^{-13}/cm^{3}$ is the location correction factor relating the fraction vented and the concentration per cm^{3} of water at the location of interest.

2. Use factor = 0.5 hours/day.

3. Environmental half-time of ^{137}Cs in the surface water is 20 days; thus, the effective half-time of ^{137}Cs in surface water is also 20 days.

B. Ingestion of water.

1. Treatment similar to item IIIB.

2. Maximum concentration of ^{137}Cs in surface water after each detonation = $10^{-9}\mu Ci/cm^{3}$; the maximum is reached on the second day following the detonation.

3. Effective half-time of ^{137}Cs in the surface water is 20 days.

V. Population

A. Demographic data included in Table 3.

B. Median age = 28 years.

C. $N^{M} = N^{F} = 5000$.

D. $w^{M} = w^{F}$.

E. w for entire population estimated at 1.3 based on current U. S. values for population size, birth rate, and life expectancy at birth.

Results of Calculations for Hypothetical Problem

The cumulative total body dose curves generated with the INREM and EXREM computer codes for all modes of exposure are shown in Figure 3. Only estimates applicable to adults are plotted for internal dose. Submersion in the radioactive cloud is unique because the exposure lasts only a relatively short time (one hour in the case of the example problem). Consequently, the radioactive half-life is used for this calculation because the source term represents an average concentration. The expected cumulative dose due to submersion in contaminated water is so low (3.5×10^{-5} mrem) that it does not appear on this graph. On the other hand, Figure 3 shows that drinking the same water results in a dose commitment of 2.2×10^{-3} mrem, almost one hundred times larger. Obviously, increasing the use factor from 0.5 hours per day for submersion in water to 2 or 3 hours per day would not result in doses even approaching those from drinking the same water. The magnitude of the differences in doses here is independent of the concentration of radioactivity in water, but is dependent on the type and energy of the radiation emitted. A similar comparison can be made of the relative hazard from submersion in a radioactive cloud and simultaneously breathing the same air. From Figure 3 it can be seen that inhalation of radioactivity results in an internal dose almost four times as great as the external dose from submersion in the radioactive cloud. It seems probable that the dose from inhalation will always be higher than the submersion dose, especially for radionuclides having a long biological half-time. The expected doses which are plotted for ingestion of contaminated food and exposure to a contaminated land surface are strictly functions of the arbitrary input parameters and are not intrinsicly related as are the dose estimates for submersion in water vs. drinking water and submersion in air vs. inhalation. It is interesting, nevertheless, to compare the expected dose (effective half-time = 1 year) from the land surface to the conservative dose (effective half-time = radioactive half-life = 30 years). Essentially all of the expected dose is accumulated by the fifth year after the initial detonation, whereas the conservative dose is considerably higher and still increasing after 60 years (the asymptotic condition is not approached until approximately 150 years). The magnitudes of the expected and conservative doses from the contaminated landscape are entirely dependent upon the arbitrary choice of effective half-times for this hypothetical case, but it raises a question that merits further consideration. For any dose integration period, what is the magnitude of conservatism of dose calculated with

$$T = T_r \text{ (conservative dose) vs. a dose calculated with } T = \frac{T_e T_r}{T_e + T_r}$$

(expected dose)? If F(t) represents the magnitude of conservatism for a specified time period due to use of the radioactive half-life only, then

$$F(t) = \frac{D_{T_r}(t)}{D_T(t)}, \qquad (20)$$

where $D_{T_r}(t)$ = cumulative external dose calculated with radioactivity loss due only to radioactive decay, and

$D_T(t)$ = cumulative external dose calculated with radioactivity losses due to environmental factors and radioactive decay.

Substituting a simple integral expression (assuming no input from parent radionuclides) for $D_{T_r}(t)$ and $D_T(t)$, we get

$$F(t) = \frac{k \int_o^t e^{-\lambda r t}\, dt}{k \int_o^t e^{-\lambda t} dt}, \tag{21}$$

where k represents all constant terms necessary to compute dose. Solution of Eq. (21) gives

$$F(t) = \frac{T_r(1 - e^{-\lambda_r t})}{T(1 - e^{-\lambda t})} \tag{22}$$

The equation for estimating the magnitude of conservatism due to exclusion of the environmental half-time in dose computations. The utility of Eq.(22) is explicit in the family of curves plotted in Figure 4 for ratios of T_r/T as large as 100/1. Figure 4 shows that after 5 years a cumulative dose calculated with $T = T_r = 30$ years would be conservative by a factor of about 3.3 when compared to a dose calculated with $T = 1$ year. The curves for land surface in Figure 3 verify this conservatism factor. Figure 4 can be used for a wide variety of assessments; its use requires no additional calculations of dose, and the time scale can be designated in any convenient time units.

A large portion of the expected dose is accrued during the year following the first detonation as shown in Figure 5. Even with the greatly expanded time scale of Figure 5 (compared to Figure 3), the dose from submersion in contaminated air appears as a step function because the total exposure time is only one hour in each case. This is in sharp contrast to the steadily increasing dose which results from inhalation during the same one-hour exposure periods. The cumulative dose from inhalation ceases to increase after a few months and this is entirely a function of the effective half-time in the body. If ^{137}Cs-^{137}Ba were taken up appreciably by bone, it might take years instead of months for the maximum dose to be attained. The remainder of the curves plotted in Figure 5 reflect the influence of environmental half-times on external exposures or the combined effects of the environmental half-times and effective half-times in the body on internal exposures.

The importance of estimating dose as a function of age when assessing population exposures has been pointed out in this paper. Example problems presented elsewhere include detailed discussions of the age-dependent parameters in the INREM code, emphasizing the need for data describing the population for which dose estimates are being made.[7,13] The input data for the INREM code for this hypothetical problem are given in Tables 1 and 2. Although the variation of one of the age-dependent parameters may appear to make it controlling (as does total-body mass in this case, see Table 1), our previous work has shown that the smaller variations of other age-dependent parameters should not be neglected when estimating expected doses for various age groups.[7,13] The accumulation of dose from internal exposure is shown in Figure 6 as a function of time and age at the start of intake. With the exception of the first exposure year, the various age groups retain their relative positions throughout the exposure period. If we assume that all age groups have equal biological sensitivity to radiation exposure, those individuals 10.5 years of age at the time of the first detonation comprise the critical population group on the basis of this analysis. While it is of interest to identify the critical population group by age, it is important in population exposure situations to identify the age at a specific point in time. These identifications are necessary because one age-dependent parameter (daily radionuclide intake) is dependent not only upon the age of the individual, but also upon the radionuclide concentrations in the intake media. Radionuclide concentrations in the intake media may vary considerably as functions of time, particularly in transient exposure situations where the concentrations attain peak values for brief periods and then decline steadily. The parameters currently programed in the INREM code as age-dependent variables undoubtedly will be shown to be functions of additional factors. For example, the effective half-time term (T_e) may require evaluation as a function of ambient temperature as well as age. As we improve our capabilities for estimating doses to populations, ever increasing specificity will be required to identify the critical population group.

The estimated genetic doses to individuals within the various age groups are given in Table 3. We assume the genetic dose is equal to the estimated total-body dose due to internal exposure plus the estimated external dose. There is very little difference among these estimated genetic doses, primarily because external exposure constitutes approximately 75 percent of the total dose; and external dose, as currently estimated with the EXREM code, is not age dependent. The genetically significant dose to the population is estimated to be 0.386 mrem, slightly exceeding the highest individual genetic dose estimate. This undoubtedly results from the assumptions used in evaluating the future child expectancy factor (w). However, one would expect the genetically significant dose to approach the individual genetic dose in this situation for two reasons: 1) every individual in the population receives approximately the same genetic dose, and 2) the median age (28 years) of the population is well below the age (50 years) assumed as the upper age limit for child bearing.

CONCLUSIONS

Estimating radiation doses to populations from Plowshare applications is a difficult and complex task. The assessment is difficult because more bioenvironmental information than is presently available is needed in order to make the assessment realistic. The desired input includes information on the source term, release and movement of radionuclides in the environment, biological and demographic characteristics of the populations exposed, and dosimetry parameters.

We believe that an important objective in assessing population exposure situations should be to derive the best estimate of the expected dose from all modes of exposure. Furthermore, knowledge of the expected dose from each important exposure mode is a prerequisite for setting specific guidelines and regulations for Plowshare applications. Such dose estimates must be made carefully for another reason--they will be scrutinized by a public that will want to know the best estimate of the dose (risk) from a given Plowshare application (benefit). There is every reason to believe that the public will be extremely interested in all Plowshare applications, and that the success of Plowshare may very well depend upon the public's acceptance of the risks involved.

Estimating expected doses requires knowledge of the deposition and redistribution of radionuclides in the environment as well as complete account of product utilization. Systems analysis offers promise for predicting the amount of radioactivity released from given Plowshare applications that may expose man both internally and externally. The systems analysis technique is well suited for this application because it is a powerful predictive tool capable of evaluating complex situations. Data already obtained from field studies can be used in systems analysis, but additional studies will have to be carried out to extend its application to Plowshare projects.

Estimation of the expected dose as a function of age is the first step toward identification of the critical population group. More data are required to evaluate the age-dependent parameters in the INREM code. These data, incomplete for many radionuclides at the present time, necessitate assumptions which lead to conservative dose estimates rather than the preferred estimates of expected dose. Currently, the critical population group, defined as that group expected to receive the highest dose, is oftentimes identified by age relative to a given point in time. As our capabilities develop for estimating population dose, consideration of additional factors influencing dose will facilitate identification of the critical population group with greater specificity.

The genetically significant dose is another important consideration in the overall evaluation of population exposures, particularly when large numbers of individuals are involved. The additional information required for this estimate is a demographic description of the population.

When all individuals within the population receive the same total expected dose, the genetically significant dose to the population approximates the genetic dose to the individual. It is unlikely, however, that the total expected doses resulting from Plowshare events will be equal for all age groups; in that case, the accuracy of the demographic information is as important as the accuracy of the age-dependent dose estimates for the ultimate estimation of genetically significant dose.

The Plowshare Program encompasses a variety of applications. Each application, and perhaps each event, will have distinguishing characteristics; thus, each will require specific radiological-safety considerations. The methods presented here represent our progress to date in developing a comprehensive methodology for assessing the potential radiation hazards to the general population. This methodology is constantly undergoing revision as a result of experience. In spite of anticipated changes in methodology, the central theme will continue to stress the best possible estimates of expected doses to the populations affected by each significant release of radioactivity to the environment.

ACKNOWLEDGMENTS

The authors are deeply indebted to William Doyle Turner of the Computing Technology Center at Oak Ridge for all the computer programming in the INREM and EXREM codes. He is also responsible for developing the mathematical approach used in the solution of the nuclear chain equations which appear in the models for external dose.

Considerable thanks are also due to E. G. Struxness and K. E. Cowser who participated in the many discussions which lead up to the formulation of this paper.

Although the contents of this paper deal with the use of peaceful nuclear detonations in general, much of the ground work was laid as a result of our participation in the radiological-safety feasibility study for constructing a sea-level canal with nuclear explosives. The feasibility study was supported by contract AT(26-1)-171 between the Battelle Memorial Institute, Columbus Laboratories, and the U. S. Atomic Energy Commission, Nevada Operations Office.

REFERENCES

1. Ng, Y. C., C. A. Burton, S. E. Thompson, R. K. Tandy, H. K. Kretner, and M. W. Pratt, 1968. Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices IV. Handbook for Estimating the Maximum Internal Dose from Radionuclides Released to the Biosphere, UCRL-50163, Part IV.

2. Kaye, S. V., and D. J. Nelson, 1968. "Analysis of Specific Activity Concept as Related to Environmental Concentration of Radionuclides," Nuclear Safety 9: 53-58.

3. Kaye, S. V., P. S. Rohwer, K. E. Cowser, and W. S. Snyder, 1969. "Predicting Radiation Dose Equivalents for Populations I. Dose Models and Methods of Application," BioScience 19: 238-41.

4. Kaye, S. V., and S. J. Ball, 1969. "Systems Analysis of a Coupled Compartment Model for Radionuclide Transfer in a Tropical Environment," pp. 731-739 in Proc. Sec. Nat. Symp. on Radioecology (Ann Arbor, Mich., May 15-17, 1967). CONF-670503.

5. International Commission on Radiological Protection, 1959. Recommendations of the International Commission on Radiological Protection (Report of Committee 2 on Permissible Dose for Internal Radiation). ICRP Pub. 2. Pergamon Press, London.

6. International Commission on Radiological Protection, 1966. Principles of Environmental Monitoring Related to the Handling of Radioactive Materials (Report of Committee 4). ICRP Pub. 7, Pergamon Press, London.

7. Rohwer, P. S., and S. V. Kaye, 1969. *Age-Dependent Models for* Estimating Internal Dose in Feasibility Evaluations of Plowshare Events. Plowshare Research and Development Progress Report for October 1, 1967 to April 1, 1968, ORNL-TM-2229.

8. Turner, W. D., S. V. Kaye, and P. S. Rohwer, 1968. EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, Report K-1752, Computing Technology Center, Union Carbide Corp., Nuclear Division, Oak Ridge, Tenn.

9. International Commission on Radiological Protection, 1964. Recommendations of the International Commission on Radiological Protection (as Amended 1959 and Revised 1962). ICRP Pub. 6, Pergamon Press, London.

10. United Nations, 1958. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, General Assembly Official Records: Thirteenth Session, Suppl. No. 17 (A/3838), New York.

11. Kaye, S. V., and P. S. Rohwer, 1968. Estimating External Dose in Feasibility Evaluations of Plowshare Events, Plowshare Research and Development Quarterly Progress Report for April 1, 1968 to June 30, 1968, ORNL-TM-2249.

12. Turner, W. D., the EXREM II Computer Code for Estimating External Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives. Report CTC-8, Computing Technology Center, Union Carbide Corp., Nuclear Division, Oak Ridge, Tenn. (In Press).

13. Rohwer, P. S., and S. V. Kaye, 1969. "Predicting Radiation Dose Equivalents for Populations II. Results Obtained with the Dose Models." BioScience 19: 326-330.

Table 1. Age-dependent parameters used in the INREM code to calculate dose to the total body.

Age (yr.)	T_e[1] (days)	ε (MeV)	M[2] (g)	f[3]		I'		
				f_a	f_w	Air[2] (cm^3/day)	Water[2,4] (cm^3/day)	Food[5] (g/day)
0-1	17	0.48	8,000	0.75	1.0	5.4×10^6	430	960
1-5	18	0.52	15,400	0.75	1.0	7.0×10^6	460	1045
5-10	30	0.54	25,100	0.75	1.0	9.7×10^6	625	1375
10-15	46	0.55	41,000	0.75	1.0	1.4×10^7	810	1520
15-20	54	0.57	65,000	0.75	1.0	1.6×10^7	950	1645
>20	61	0.59	70,000	0.75	1.0	1.7×10^7	1000	1260

[1] T. F. McCraw, Radiological Health Data and Reports, 6, 711 (1965).

[2] P. S. Rohwer and S. V. Kaye, *Age-Dependent Models for Estimating Internal Dose in Feasibility Evaluations of Plowshare Events*, ORNL-TM-2229 (April 1968).

[3] International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publ. 2, Pergamon Press, London (1959). The ICRP values for adult workers are applied to all age groups in the absence of information on the possible age dependence of these absorption factors.

[4] Modified to include only the daily intake of tap water and beverages based on tap water.

[5] Agricultural Research Service, *United States Department of Agriculture Family Economics Review*, Consumer and Food Economics Research Division (October 1964).

Table 2. Ingestion of ^{137}Cs (pCi/day) in food as a function of time after the first detonation.

Time after the first detonation	pCi/day intake in food at any time for individuals in each age class.					
(days)	(0-1 yr)	(1-5 yr)	(5-10 yr)	(10-15 yr)	(15-20 yr)	(>20 yr)
0	0	0	0	0	0	0
1	.0096	.010	.014	.015	.016	.013
2	.019	.021	.028	.030	.033	.025
3	.029	.031	.041	.046	.049	.038
4	.038	.042	.055	.061	.066	.050
5	.048	.052	.069	.076	.082	.063
6	.058	.063	.082	.091	.098	.076
7	.077	.084	.11	.12	.13	.10
8	.13	.15	.19	.21	.23	.18
9	.27	.29	.38	.42	.46	.35
10	.46	.50	.66	.73	.79	.60
11	.69	.75	.99	1.09	1.18	.91
12	.86	.94	1.24	1.37	1.48	1.13
13	.94	1.02	1.35	1.49	1.61	1.23
14	.96	1.04	1.38	1.52	1.64	1.26
30	.93	1.01	1.33	1.47	1.60	1.22
31	.94	1.02	1.34	1.49	1.61	1.23
32	.95	1.03	1.36	1.50	1.62	1.24
33	.95	1.04	1.37	1.51	1.64	1.25
34	.96	1.05	1.38	1.52	1.65	1.26
35	.97	1.06	1.39	1.54	1.66	1.27
36	.98	1.06	1.40	1.55	1.68	1.28
37	1.0	1.08	1.42	1.58	1.70	1.31
38	1.05	1.14	1.50	1.66	1.80	1.38
39	1.18	1.29	1.70	1.87	2.03	1.55
40	1.37	1.50	1.97	2.18	2.36	1.80
41	1.60	1.74	2.30	2.54	2.75	2.10
42	1.77	1.93	2.54	2.81	3.04	2.33
43	1.85	2.01	2.65	2.93	3.17	2.43
44	1.87	2.03	2.67	2.95	3.20	2.45
224	1.32	1.44	1.90	2.10	2.27	1.74
409	.93	1.01	1.33	1.47	1.60	1.22
589	.66	.72	.95	1.05	1.14	.87
774	.47	.51	.67	.74	.81	.62
1139	.23	.25	.33	.36	.39	.30
1504	.12	.12	.16	.18	.20	.15
1864	.058	.063	.082	.091	.099	.076
3650	.0019	.0021	.0028	.003	.0033	.0025
7300	0	0	0	0	0	0

Table 3. Table of information relative to genetic dose.

k (years)	d_k[1] (mrem)	N_k[2]	w_k[2]	$d_k \times N_k \times w_k$
0-1	0.347	180	2.74	171
1-5	0.336	800	2.74	737
5-10	0.365	1,050	2.74	1,050
10-15	0.379	1,000	2.74	1,040
15-20	0.360	900	2.73	885
20-25	0.355	740	2.38	625
25-30	0.355	600	1.45	308
30-35	0.355	550	0.70	137
35-40	0.355	600	0.27	58
40-45	0.355	600	0.06	13
45-50	0.355	560	0.004	1
50-55	0.355	570	0	0
55-65	0.355	890	0	0
65-75	0.355	600	0	0
75-85	0.355	300	0	0
>85	0.355	60	0	0
		10,000		5,025

[1] The total dose (external exposure + internal exposure) accumulated to age 50 years, the age assumed to be the upper limit for child bearing.

[2] Calculated with information obtained from: U. S. Bureau of Census, *Statistical Abstract of the United States*, 1968 (89th edition), Washington, D. C. (1968).

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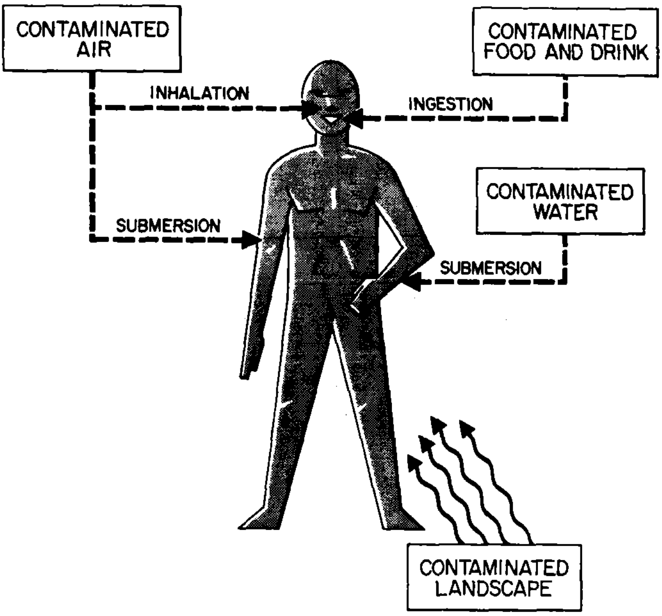

Modes of Exposure

Figure 1. Modes of Exposure.

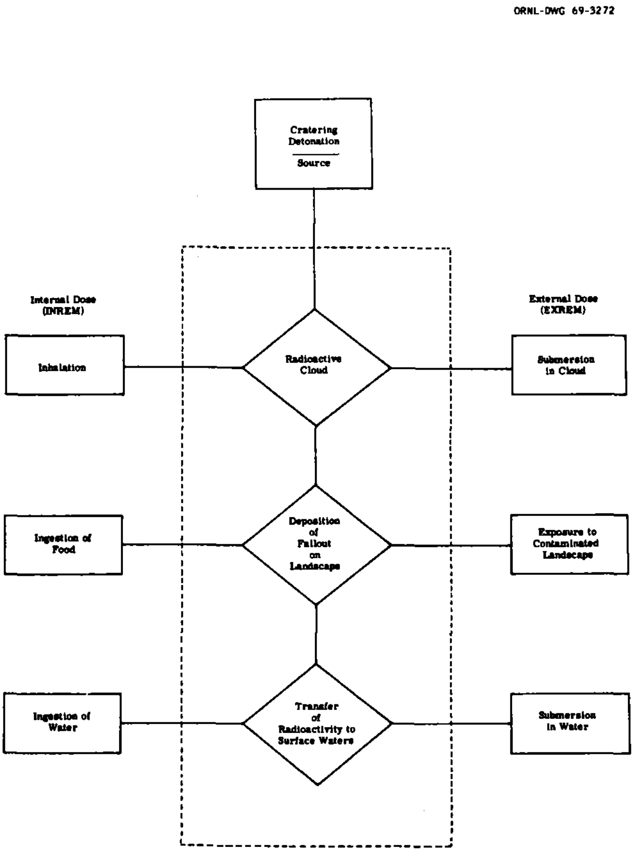

Figure 2. Simplified Block Diagram of Hypothetical Problem.

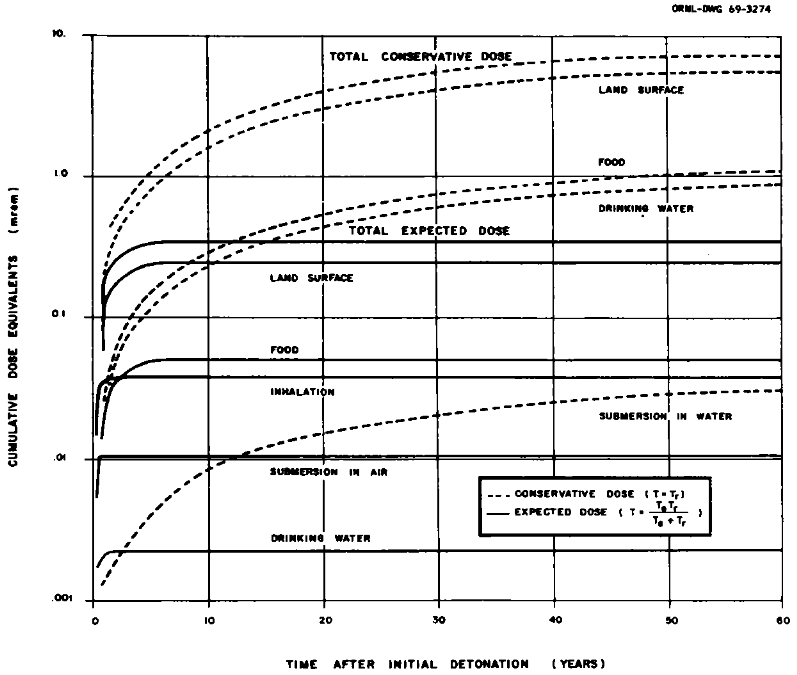

Figure 3. Doses Accumulated in the Period 0-60 Years Following the First Detonation for the Hypothetical Problem.

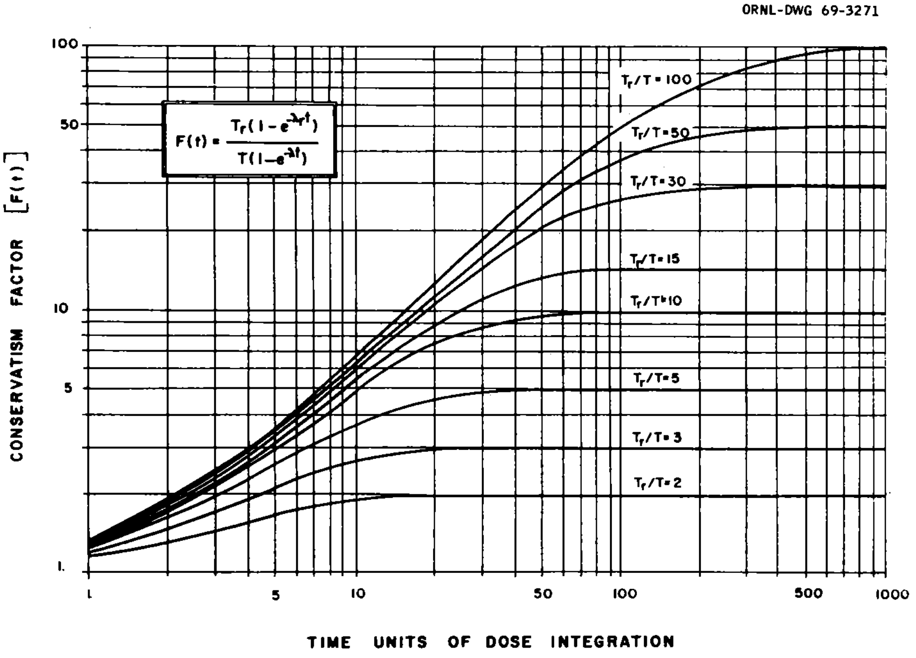

Figure 4. Graph of Conservatism Factors for External Dose Estimates Utilizing Radioactive Decay as the Only Process Which Reduces the Radiation Field.

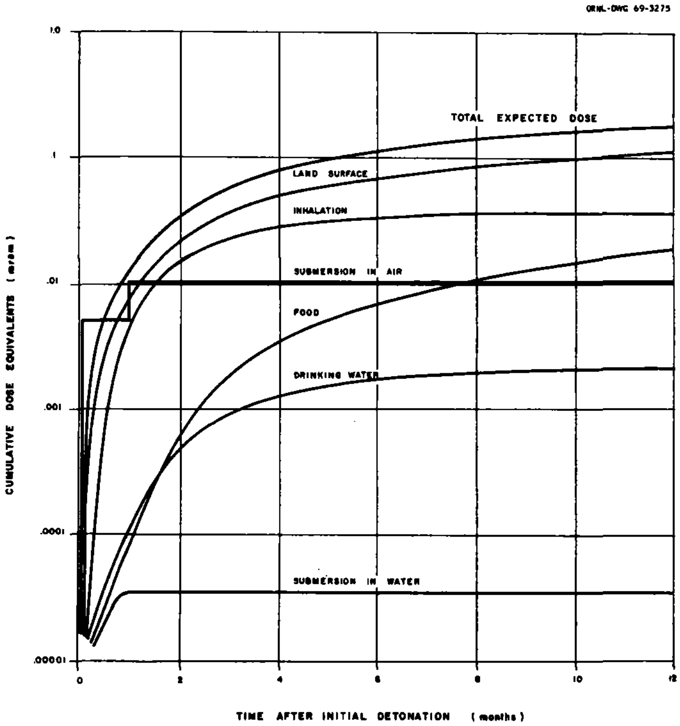

Figure 5. Doses Accumulated in the First Year Following the First Detonation for the Hypothetical Problem.

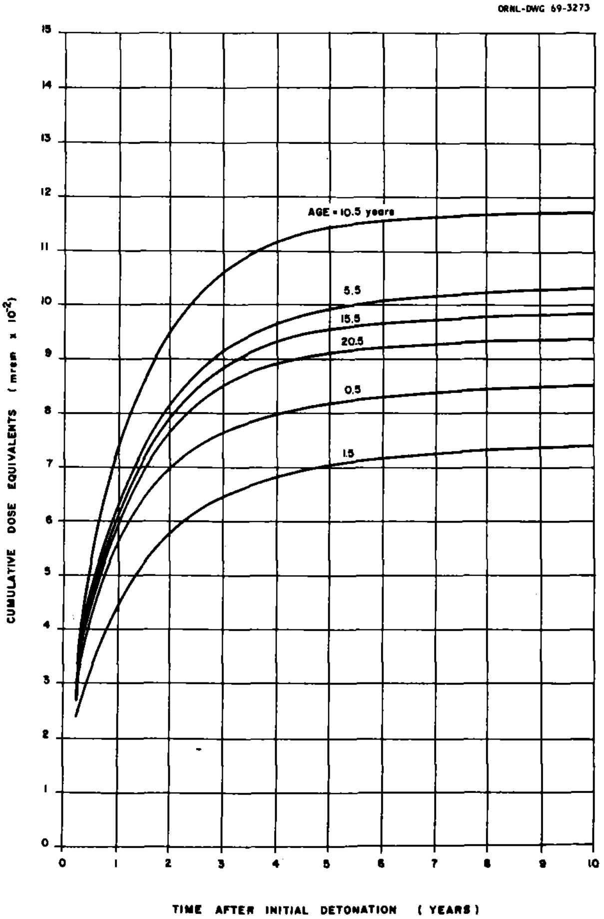

Figure 6. Age-Dependent Variation in Internal Dose During the Period 0-10 Years Following the First Detonation for the Hypothetical Problem.

QUESTIONS FOR STEPHEN KAYE

1. From C. E. Nelson

In your discussion, what "dose" were you talking about, skin dose, gonade dose, "whole-body dose," lung dose, or what? To what structure does "cumulative dose" refer?

ANSWER:

The radionuclide we were dealing with was cesium-137 and the critical body organ for this nuclide is total body. So these were total body doses.

2. From Frank Lowman:

Microgram and microcurie frequency distributions of trace elements and radionuclides in plants and marine animals are log-normal extending over an order of magnitude or more in most populations. Tipton's and Foster's data suggest that this may also be true for humans. How would one adjust considerations of Standard Man to protect the 3 to 10% of the population group concentrating 5 to 7 times the arithmetic mean amount of a radionuclide concentrated by individuals of the population?

ANSWER:

You better send this one to the ICRP. This really is not a problem which we are able to deal with right now since, as Dr. Lowman has pointed out, this is true that most all of these measurements of stable elements in the biota and in the different organs of man are known to follow the log-normal distribution and, of course, this can be handled nicely statistically, but there is this part of the population then which would be neglected when we are calculating doses based on the mean individual. I think that this problem has been discussed by Dr. Tipton who has conducted most of the analyses for Standard Man and I know it's something that she continues to work on, in fact, she has various models which show the statistical distribution of these concentrations in various populations. I don't think this problem actually comes under the heading of this paper and I would be glad to refer it to Dr. Tipton at some time for you, Dr. Lowman. This really is in her area and the ICRP. It's not up to one individual, I think, to comment on something like this.

3. From Robert Patzer:

Does the EXREM Code include inhalation of radioactive material from dry fallout which is re-suspended in air--for example by wind?

ANSWER:

The EXREM Code deals only with the external exposure, the radioactivity which is outside the body. If the radioactivity is resuspended, then we would calculate the dose due to inhalation, if it's taken back into the body, using the INREM Code.

4. From Robert Patzer:

Does the INREM Code handle intake of radionuclides from contaminated consumer products? For example--contaminated natural gas to food and air in a home.

ANSWER:

Yes, the input to the INREM Code is microcuries per day and it makes no difference what the medium is--whether it's water, food, it could even be with a slight little change in the model or the way we put the input information in, it could be through a wound.

5. From S. G. Bloom:

You stressed age dependency in the INREM Code. What about the dependency on intake rate? In particular, aren't f_{in} and λ_{in} functions of intake rate? What are the relative errors in neglecting intake dependency versus age dependency? How do these errors compare with the uncertainty in the biological parameters?

ANSWER:

As the Code is now written, the lambdas are not a function of the intake rate, so wherever this is known to influence the elimination rate, we have not taken this into consideration. You have to understand that this a very general, working-type model which is not intended for any one little, specific application, like if you were only dealing with one pathway of exposure. If you were specializing in that with one radionuclide, you would develop a specialized model for that. But we're talking about a model which will handle hundreds of radionuclides, many different modes of exposures and it also considers all of the detonations so that we cannot write a model which would restrict its use. Therefore, it has to be general. But when we do have data on parameters, then we can make changes in the program. No computer program, as far as I am concerned, is ever final. We are always updating this and our limitations here in this internal program are that we cannot find the necessary parameters for let's say most of the radionuclides as a function of age of the individual. We have it for tritium, for cesium, for strontium, for iodine. When we get out of that small little group, then we have some information, but we have to fill in with conservative estimates or sometimes we fill in with the Standard Man values. But I'm sure that as time goes on, we will get more and more information so that we will be able to calculate the age dependent dose for many more radionuclides. This is our hope.

EXPOSURE-DOSE RESEARCH FOR RADIONUCLIDES IN NATURAL GAS

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ABSTRACT

The fate determination of specific radionuclides in natural gas stimulated by underground engineering applications is being examined. An experimental program, now in its initial stages, is using gas artificially labeled with krypton-85 and tritium under simulated domestic situations. The following topics are being investigated in this study:

1. *The concentration of the radionuclides in a gas-heated home.*
2. *The build-up of contamination on appliances in the kitchen environment.*
3. *The concentration in foods as a function of radionuclide, food type and preparation.*
4. *The maximum exposure plausible under specified conditions.*

INTRODUCTION

Since its beginning, the Plowshare program has moved steadily forward from the initial cratering concepts for canals, mountain passes, harbors and dams to underground engineering application concepts such as economical methods for enhancing the recovery of petroleum, minerals and gas. It is in this latter category, i.e., underground engineering applications, that we have addressed this study. More specifically, we are directing our initial research program at investigating certain parameters of natural gas from the Gasbuggy cavity. Gas field applications are being considered first because of their advanced status relative to petroleum products and minerals, proximity of users to the product, and the relatively short time from production to user.

Project Gasbuggy, conducted jointly by the U. S. Atomic Energy Commission, the El Paso Natural Gas Company, and the U. S. Bureau of

Mines was a nominal 26-kiloton nuclear explosive detonated on December 10, 1967, some 4,200 feet below the floor of the San Juan Basin in New Mexico. In addition to objectives of determining production enhancement and developing prediction capability and technical engineering knowledge, an additional goal of the experiment was the determination of the gas quality with respect to radioactivity. It should be noted that Project Gasbuggy was an experiment and gas from the stimulated and surrounding wells is not being distributed to any consumer.

A fission device would be expected to yield such particulate contaminants as cesium-137 and strontium-89, but the majority of such particulates would settle out or be filterable before use of the gas in any commercial or domestic application. Gas cleaners are usually required in a production plant to remove dust and solids in the lines. Filters, liquid bath scrubbers and dry cyclone scrubbers are types normally used and can have efficiencies for particulate material upwards of 99%. Many field production systems also use gas and liquid separators which collect liquid droplets from the stream.[1]

In addition, certain gaseous contaminants would probably be present. Some of the major gaseous isotopes resulting from a fission event are iodine-131, xenon-133 and krypton-85. All but krypton-85 have short half-lives, i.e., eight days or less, and could be allowed to decay prior to use of the gas. Krypton-85, with its 10.3-year half-life, can be expected to be produced at about 20 Ci/kt for a typical fission explosive.[2] The activation product, carbon-14 (5,568-year half-life), may also be produced in certain applications in sufficient quantities to warrant consideration.

A fusion device could yield tritium (12.3-year half-life) up to amounts of about 5×10^4 Ci/kt.[3] Concentrations in Gasbuggy gas from 1 to 7 months post-event remained at about 17 μCi/ft^3 normal temperature and pressure (NTP) for tritium, and 2.8 μCi/ft^3 NTP for krypton-85.[4]

OBJECTIVES

The research project recently initiated at the Southwestern Radiological Health Laboratory is directed at determining the ultimate fate of those radionuclides in gas which, because of their half-life and concentration, could be of concern, e.g., tritium, krypton-85 and perhaps carbon-14. The two major objectives of this study are:

1. To develop human exposure and/or dose estimates from experimental data such as:
   a. Concentration of radionuclides in various foods prepared under realistic conditions on or in a gas range.

b. Concentration of radionuclides in a home where unvented gas appliances such as space heaters, dryers, water heaters, refrigerators and ranges are used.

c. Buildup of the contamination on appliances and home surfaces in the vicinity of the combustion equipment.

2. To suggest values for radiation concentration guides for specific radionuclides in gas $(RCG)_G$ for commercial and domestic use.

CALCULATIONS

There are several calculations which may be performed to yield a suggested $(RCG)_G$ for tritium in natural gas. Some of them, particularly those which rely on consumer habits and habitat, are fraught with assumptions. Variations in assumptions for the number, design and use of the different domestic gas appliances and in dilution volume and ventilation rates for a home can induce a wide range in derived $(RCG)_G$ values.

In this report the term specific tritium activity is defined as the tritium concentration per gram of protium (µCi/g hydrogen). Two calculations are presented which extend the calculation to a theoretical limit because of the assumption of maximizing the specific tritium activity in man and his food water. They are used to highlight areas where experimental measurements are essential. The calculations are performed first for a continuous occupational exposure situation and then the $(RCG)_G$ for the general population is discussed.

The first of these calculations considers only ingestion of tritium via water in foods and beverages prepared on or in a gas range. The maximum permissible concentration of tritium in water $(MPC)_w$ for continuous occupational exposure as accepted by the International Commission for Radiological Protection (ICRP) and the National Committee on Radiation Protection (NCRP) is 0.03 µCi/cm^3.[5,6] The ICRP report also cites 2,200 cm^3/day[7] as the water intake through food and fluids for a standard man. The standard man could then continuously ingest 0.03 µCi/cm^3 x 2,200 cm^3/day or 66 µCi/day as tritium oxide (HTO) in his food and water. However, only that portion of his food which is cooked is assumed to contain tritium, and at concentrations dependent on its water content.

The standard man's water intake is assumed to be distributed between three classes of food:

1. Meat, fish and poultry (m, f, p)
2. Beverages (b)
3. Vegetables (v)

A sampling of 31 vegetables and 36 various "main course items," i.e., meat, fish or poultry, from a USDA[8] listing shows that the average water content for the cooked vegetables is about 88% and for the cooked meats, poultry and fish about 51%. The per capita diet in the United States for 1967[9] shows that the average daily individual consumption is approximately 270 grams of meats, fish and poultry, all of which are assumed to be cooked for the purpose of this calculation. In addition, 404 grams of vegetables are eaten daily of which 80% is assumed to be cooked. Coffee, tea and cocoa in the powder form are about 3.2% water and average about 98% water content as beverages. The 18.8 grams of powder consumed daily is equivalent to 18.2 grams dry or 910 grams as beverages.

If a tritium intake of 66 µCi/day from cooked food water is permissible then the acceptable concentration in food water is:

$$(\mathrm{MPC})_w \quad \left(0.03\ \frac{\mu\mathrm{Ci}}{\mathrm{g}}\right) \times \frac{\text{Total } H_2O \text{ intake (2,200 g)}}{H_2O \text{ intake from cooked foods (1312 g)}} = 0.05\ \frac{\mu\mathrm{Ci}}{\mathrm{g}}$$

For a particular class of food the projected intake rate would be:

0.05 µCi/g × fraction by weight of H_2O × consumption (g/day) = µCi/day

The tritium can be distributed over that portion of the diet assumed to be cooked in the following manner:

0.05 µCi/g × 0.51 (water content) × 270 g (m,f,p/day) = 6.93 µCi/day
0.05 µCi/g × 0.88 (water content) × 323 g (v/day) = 14.26 µCi/day
0.05 µCi/g × 0.98 (water content) × 910 g (b/day) = 44.81 µCi/day
Total 66.00 µCi/day

The specific tritium activity in a given food will depend on the amount of tritium that is exchanged with protium in the food solid and water. The maximum value would be obtained in the hypothetical case of assuming that all of the hydrogen is exchangeable and allowing the exchange to equilibrate. In this first calculation we assume that only hydrogen in the water fraction exchanges and that there is no tritium enrichment factor introduced by a concentration mechanism in the food.

For the combustion reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

the tritium in the gas is expected to be completely converted to HTO. The combustion of each standard cubic food (scf) of CH_4 (0.7168 g/l) yields 45.7 g of H_2O. The tritium concentration in the gas necessary to yield the $(\mathrm{MPC})_w$ value in body water under the foregoing assumptions would be:

$$\frac{45.7\ \mathrm{g\ H_2O}}{\mathrm{scf\ CH_4}} \times \frac{0.05\ \mu\mathrm{Ci}}{\mathrm{g\ H_2O}} = 2.28\ \mu\mathrm{Ci/scf\ CH_4}$$

The second calculation, based on maximizing the specific tritium activity in man, is broader in scope but only slightly more restrictive. The major assumption is that the specific tritium activity in any human exposed to the gas combustion products could not, in the absence of any enrichment mechanism, exceed the specific activity in the gas. This is true for infinite inhalation, ingestion and absorption insult.

Hydrogen accounts for about 10% by weight of the human body, and the limiting specific activity can be calculated from the maximum permissible body burden for occupational exposure, i.e., 10^3 µCi. For a 70 kg man this amounts to 0.14 µCi/g of hydrogen. Since a standard cubic food of CH_4 weighs 20.3 grams of which 5.08 grams are hydrogen, the theoretical limiting concentration is:

$$0.14\ \mu\mathrm{Ci/g} \times 5.08\ \mathrm{g\ of\ H/scf\ of\ gas} = 0.71\ \mu\mathrm{Ci/scf\ of\ gas}$$

Since a large fraction of a population could be exposed to radionuclides by extensive application of gas field stimulation programs, the general population genetic dose guide of 5 rem/30 years or 0.17 rem/year is applicable.[10] This guide is 1/30 of the occupational guide of 5 rem/year. The values in the gas from the two calculations become:

$$(\mathrm{RCG})_G\ (\text{based on limiting Sp}^3\text{H activity in food water}) = 1/30\ (2.28 \times 10^6\ \mathrm{pCi/scf}) = 7.6 \times 10^4\ \mathrm{pCi/scf}\ (\mathrm{CH_4})$$

and

$$(\mathrm{RCG})_G\ (\text{based on limiting Sp}^3\text{H activity in body protium}) = 1/30\ (0.71 \times 10^6\ \mathrm{pCi/scf}) = 2.4 \times 10^4\ \mathrm{pCi/scf}\ (\mathrm{CH_4})$$

If we had applied (a) the correction factor of 0.1 recommended by the NCRP[11] and in Title 10, Code of Federal Regulations, Part 20[12] for permissible levels of radiation in unrestricted areas and (b) a correction factor of 1/3 suggested in the Code of Federal Regulations for time averaging of suitable samples of the population, then the same guide of 1/30 would be applicable.

The foregoing calculations are, like other RCG calculations, inherently limited because of assuming there is no additional internal or external dose contribution from other radionuclides. Neither of the two values is presented to suggest a maximum permissible concentration of tritium in gas but rather to suggest a point of departure for the calcultion of realistic values. The values calculated are very conservative because they are based on the worst possible condition, that of the specific tritium activity in man or his diet attaining the same value as that in the gas. Although these values would give assurance that individuals in the population would not receive radiation doses from tritium in excess of appropriate limits, they may lead to unreasonable limitations in the development of nuclear energy utilization.

STUDY DESIGN

The studies at the Southwestern Radiological Health Laboratory are designed to yield experimental data which can be used as input for realistic $(RCG)_G$ values for each of the radionuclides of concern. The philosophical considerations in setting a reduction factor for use of the gas by the general public are beyond the scope of this study.

The experimental program recently has commenced with the setting up of a small 2,000-cubic foot laboratory which contains six fume hoods, each having an exhaust capacity of about 1,000 cubic feet-per-minute. A conventional domestic gas range has been installed with a metered inlet manifolded to allow for either contaminated or clean gas to enter the combustion chambers. The gas pressure and flow rate are recorded throughout an experiment. The range burners themselves are equipped with electronic ignition to eliminate problems associated with a pilot light.

Commercially available technical grade CH_4 which contains 5 µCi/scf tritium in one case and 5 µCi/scf krypton-85 in the other, was procured for the initial phases of the study. The original plans to use gas from the Gasbuggy cavity had to be altered for a number of reasons. Although pre-shot methane levels were in excess of 85%, in samples one to seven months post-shot methane accounted for only 37 to 44% of the total gas in the cavity. Carbon dioxide levels, originally less than 1% were then about 36%.[4] Finally, some post-shot gas samples contained up to about 0.18% of H_2S.[13] The gas would require processing prior to being put to representative use. Plans to use the cavity gas, after processing, are being considered for later in the program.

The actual laboratory studies using a contaminated gas have begun and data will be forthcoming shortly.

1. Water heated in uncovered vessels in the oven and on a top burner is being used to establish the range of radioactive concentrations that may be encountered in food cooked with contaminated methane. The time required for the concentration to equilibrate can be measured simultaneously.

2. Foods which represent constituents in man's diet are being prepared under both typical and extreme conditions to evaluate contamination mechanisms.

3. Cryogenic samplers and liquid bath scrubbers are being used to measure air concentrations. High efficiency filters collect that portion of the contamination associated with particulates. Some exploratory work will have to be conducted to optimize the collection efficiencies for each of the radionuclides.

The preceeding calculations emphasized the requirement for data on tritium-protium exchange coefficients, equilibrium conditions and exchange rates. Air concentration measurements for carbon-14, krypton-85 and tritium upon contaminated methane combustion are also considered essential input to $(RCG)_G$ evaluations. We hope that in conducting some of these measurements the magnitude of the potential exposure will be established and a comprehensive calculation of the $(MPC)_G$ can be undertaken.

Our preoccupation with tritium in this presentation is not meant to imply an estimate of the relative importance of the radionuclides considered. Depending on the design and environment of the nuclear device, tritium or some other radionuclide could be the limiting nuclide.

REFERENCES

1. Francis, Jr., A. W. and Morris, R. L. Gas Separators, Heaters, and Cleaners. In: Gas Engineers Handbook, pp. 4/63-4/67, The Industrial Press, 1966.

2. Ward, D. C., Atkinson, C. H. and Watkins, J. W. Project Gasbuggy--A Nuclear Fracturing Experiment. Journal of Petroleum Technology, pp. 139-145, February, 1966.

3. Jacobs, D. G. Sources of Tritium and Its Behavior upon Release to the Environment. AEC Critical Review Series, U. S. Atomic Energy Commission/Division of Technical Information, p. 24, 1968.

4. Smith, C. F. and Momyer, F. F. Gas Quality Investigation Program Status Report for Project Gasbuggy. PNE-G-10, Lawrence Radiation Laboratory, September 18, 1968.

5. Report of Committee II on Permissible Dose for Internal Radiation, Recommendations of the International Commission of Radiological Protection, ICRP Publication 2, p. 41, Pergamon Press, 1959.

6. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure, Recommendations of the National Committee on Radiation Protection, National Bureau of Standards Handbook 69, p. 24, U. S. Government Printing Office, June 5, 1959.

7. Report of Committee II on Permissible Dose for Internal Radiation, Recommendations of the International Commission on Radiological Protection, ICRP Publication 2, p. 152, Pergamon Press, 1959.

8. Watt, B. K. and Merrill, A. L. Composition of Foods. In: Agriculture Handbook No. 8, pp. 6-67, U. S. Government Printing Office, 1963.

9. Agricultural Statistics--1968, U. S. Department of Agriculture, p. 597, U. S. Government Printing Office, 1968.

10. Background Material for the Development of Radiation Protection Standards, Staff Report of the Federal Radiation Council, Report No. 1, U. S. Department of Health, Education and Welfare, Section V, 5.5, p. 27, May 13, 1960.

11. Maximum Permissible Body Burdens and Maximum Permissible Concentration of Radionuclides in Air and in Water for Occupational Exposure, National Bureau of Standards Handbook 69, p. 6, U. S. Government Printing Office, June 5, 1959.

12. Code of Federal Regulations, Title 10--Atomic Energy, Office of the Federal Register, National Archives and Records Service, General Services Administration, p. 129, January 1, 1967.

13. Project Gasbuggy--Well Test Data September 1967 to September 1968, Volume II, p. 245, El Paso Natural Gas Company.

QUESTIONS FOR DAVID N. McNELIS

1. From C. E. Nelson:

   How and when does tritium migrate from gas to food? During cooking? During the cooling phase in the room after cooking has stopped? Both?

   ANSWER:

   We do not have any experimental data to present at this time. However, I would think that both in varying amounts would be appropriate.

2. From Walt Kozlowski:

   You stated that one of the goals of Gasbuggy was the determination of the gas quality with respect to radioactivity. You then set about determining acceptable radioactive levels. What cost factor would be required to process Gasbuggy gas to meet these levels? And is so much processing required that Gasbuggy type developments are not feasible?

   ANSWER:

   Of course Gasbuggy was an experiment, and the gas from it is not intended for consumer use. As far as this pertains to other stimulation events, I think that this question would be more appropriately put to other agencies.

THE FATE AND IMPORTANCE OF RADIONUCLIDES PRODUCED IN NUCLEAR EVENTS[*]

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ABSTRACT

Some of the major programs at the Bio-Medical Division concerned with the fate and importance of the fission products, the radionuclides induced in the device materials, the radionuclides induced in the environment surrounding the device, and the tritium produced in Plowshare cratering events will be discussed.

These programs include (1) critical unknowns in predicting organ and body burdens from radionuclides produced in cratering events; (2) the analysis with a high-resolution solid state gamma ray spectrometer of radionuclides in complex biological and environmental samples; (3) the characterization of radioactive particles from cratering detonations; (4) the biological availability to beagles, pigs and goats of radionuclides in Plowshare debris; (5) the biological availability to aquatic animals of radionuclides in Plowshare and other nuclear debris and the biological turnover of critical nuclides in specific aquatic animals; (6) the biological availability of Plowshare and other nuclear debris radionuclides to dairy cows and the transplacental transport of debris radionuclides in the dairy cow; (7) the persistence and behavior of radionuclides, particularly tritium, at sites of Plowshare and other nuclear detonations; and (8) somatic effects of Low Dose Radiation: Chromosome studies.

INTRODUCTION

The major objectives of the Bio-Medical Division at the Lawrence Radiation Laboratory at Livermore are:

1. To develop a predictive ability for estimating the impact of the release of radiation and radionuclides upon the biosphere,

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[*] This research was performed under the auspices of the U.S. Atomic Energy Commission.

and in particular upon man, from any credible type of nuclear event: reactor releases, reactor accidents, nuclear accidents, nuclear testing, nuclear war, or peaceful uses of nuclear explosives.

2. To utilize the developing predictive ability to minimize the radiation burden to man from nuclear events, planned or unplanned, during the period pending development of a mature and complete predictive ability.

3. To develop appropriate countermeasures for credible nuclear events at any step along the route from the source of radionuclides to man, with the objective of minimizing the radiation burden to man before or after access of the radionuclides to his tissues.

4. To evaluate the bioenvironmental feasibility of planned Atomic Energy Commission utilization of nuclear explosives for peaceful purposes, such as Plowshare events.

5. To determine the effects of radiation on man - in particular the effects of chronic exposure to low doses of radiation or moderate doses delivered at low rates.

The four main divisions of our program are (1) the prediction before each event, on a global basis, of the ultimate body and organ burden likely to be delivered to man by external radiation and by each of the radionuclides likely to be produced in the event; (2) the documentation or quantitation of the life history of the radionuclides produced in the event; (3) the determination of any effects on man of radiation from internal and external sources; and (4) the development of countermeasures to minimize any radiation burden to man.

Many of our major programs are directly involved in research on the fate and importance of radionuclides produced in Plowshare events. Each of these could well be the subject of a 30- to 40-minute presentation, but because of time I can present only highlights and representative portions of several of these programs. The programs discussed today are described in greater detail in the published text of this Symposium. They and other programs are described fully in publications from the Division and in those that are presently in press.

PREDICTION OF ORGAN AND BODY BURDENS FROM RADIONCULIDES PRODUCED IN PLOWSHARE EVENTS

We have developed a method for estimating the total maximum internal dose to the whole body and organs of man and the contribution of individual radionculides to this dose. This program has been so designed that the predictive approach allows us to supply quantitative guidelines at three important phases of the Plowshare Excavation Program:

1. In preshot rad-safe analysis, we can determine whether or not a particular event can be conducted without exceeding existing tolerances.

2. In guidance for postshot documentation, we can indicate what should be measured, where it should be measured, and with what precision it should be measured.

3. In guidance for device design, we can indicate the maximum amount of a radionuclide that can be produced and subsequently released to the environment without exceeding prescribed tolerances.

This predictive approach is described in a series of reports. The first part presents the approach used to estimate the fallout levels as a function of cloud travel time for periods up to 50 hours after detonation. In the second, we show how these fallout estimates can be combined with radionuclide production estimates and biological uptake relationships to arrive at estimates of burden and dosage for man. The third part shows how this predictive approach can supply guidelines for the design of nuclear devices for peaceful purposes.

The fourth part is a handbook which lists the input parameters required for the estimation of dosage. When considering the public health and safety, one must not underestimate the dosage that can be delivered to man and his organs after detonation. It is also important not to overestimate the dosage, and as data become available from other Division programs in such critical areas as the fraction of certain radionuclides released to the atmosphere on small particles (<50 μ in diameter) and the availability in certain biological systems of certain radionuclides, the estimates of some radionuclide dosages will be replaced by more appropriate values. For many radionuclides, our experimental programs have used debris from Plowshare cratering events to generate the appropriate data.

The last two parts of the series present our approach for predicting the dosage to man from aquatic foodstuffs and an analysis of the transport of nuclear debris by surface and groundwater.

The four major sources of radioactivity from a typical Plowshare cratering event are fission products, neutron activation of the environment, neutron activation of the device, and tritium. Estimates have been made of the organ and body burdens from each of the radionuclides produced in each of these sources of radioactivity. Examples of these estimates are presented in Tables I and II. Table I presents the estimated maximum dosage to the child's whole body and bone from plutonium-239 fission products, assuming wet deposition by rainout at 12 hours after detonation. Table II presents the estimated maximum dosage via milk to the child's whole body and bone from activation products produced in granite by neutrons, also assuming a wet deposition by rainout at 12 hours after detonation. It is to be emphasized that these values represent the estimated maximum dose as a consequence of wet deposition by rainout and that a maximum deposition via dry deposition would lower these estimates by more than an order of magnitude.

Another application of our approach deserves comment. Using this approach, concentrations were estimated of certain radionuclides in grass and milk following a nuclear test that was presumably some 7000 to 8000 miles away. The estimated and measured concentrations are presented in Table III. The close correspondence between the estimated and measured values indicates the overall capability of this approach.

SOLID-STATE DETECTORS IN THE QUANTITATION OF GAMMA-EMITTING RADIONUCLIDES IN BIOLOGICAL AND ENVIRONMENTAL SAMPLES

Several programs in the Division are concerned with quantitating the life history of the radionuclides that interact with the biosphere. Essential to these programs has been the development of a high-resolution, anticoincidence-shielded gamma spectrometer to analyze complex, low-level mixtures of gamma-emitting radionuclides in environmental and biological samples.

Formerly, gamma-emitting radionuclides in environmental and biological samples could be determined only by techniques involving radiochemical separation followed by spectrometry with sodium iodide scintillators. These techniques were frequently so laborious and time consuming as to discourage the extensive samplings required in Plowshare experiments. There is no doubt that the introduction of the solid state lithium-drifted germanium [Ge(Li)] detector has revolutionized gamma ray spectroscopy, primarily because of its striking improvement in spectral resolution over the sodium iodide detector. This advantage is illustrated by a complex gamma ray spectrum (Fig. 1) from particulate fallout, presumably from a Chinese test, counted on the filter paper on which it was collected. The usefulness of this spectrometer in biological experiments is illustrated also in Figure 2, which shows spectra from samples of feces, plasma, milk and urine from a dairy cow 24 hours after it was fed radioactive debris obtained at the site of a nuclear detonation. Radiochemical separation and purification were not required to obtain these data.

This spectrometer (Fig. 3) has given excellent resolution and at the same time has been highly efficient in the assay of large volume as well as small volume samples. Other gamma ray spectrometers with Ge(Li) detectors and anticoincidence shielding have been reported in the literature. While they may serve the purposes for which they were designed, none has achieved as high resolution and sensitivity in counting small as well as large samples (e.g., up to 200 ml) as the spectrometer developed by us. It can quantitatively analyze radionuclides with specific activities of as little as 0.02 picocuries per gram of material present either alone or as a part of a complex mixture of radionuclides. It is particularly suitable for rigorous studies of the slow incorporation of low levels of radionuclides into biological or environmental systems.

Four special features of the spectrometer contibute to its excellence:

1. The incorporation of a planar Ge(Li) detector of large surface area (6 cm x 3 cm) and one centimeter depletion depth, developed especially for this spectrometer.

2. The Ge(Li) detector is surrounded by a plastic phosphor (anticoincidence) shield, and the two are operated in anticoincidence to reduce the Compton continuum. This enhances the weak spectral lines and consequently improves the sensitivity.

3. Inside the vacuum chamber, a cooled first-stage field-effect transistor (FET) preamplifier adjacent to the Ge(Li) detector insures maximum resolution.

4. The anticoincidence and coincidence spectra are recorded separately to improve the counting sensitivity for radionuclides whose decay schemes involve coincident events.

Our research on solid state detectors is continuing. Significant progress has been made in establishing a reliable basis for selecting high-quality germanium for large volume Ge(Li) detectors. A set of standard tests has been devised that has resulted in high yields of good detectors. It is now practical to consider a whole-body animal counter with eight 20-square-centimeter detectors. This would represent a truly significant advance in whole-body counting. We are also developing a Ge(Li) detector system for field use in conjunction with Plowshare excavation experiments. A field laboratory, trailer-housed, will have a counting system with a super-insulated cryogenic system to maintain the Ge(Li) detector at -185°C. This is necessary to insure low consumption of liquid nitrogen under field conditions.

As the applications of nuclear energy increase, man will be continuously exposed to radiation from the released radionuclides that become localized in his body. Accordingly, one of the most crucial problems will be to assess the effects upon man of low or moderate doses of radiation delivered at very low rates. It has been suggested that exposure to 10 rads may cause biological harm under some circumstances. But what about lower doses? *Is all radiation harmful? Should the extrapolation* to a zero-rad dose be linear or curvilinear? If it should turn out that the correct extrapolation is a linear one, then it will be crucial to determine very accurately at very low levels the radionuclide content of man's food and water. Such data on gamma-emitting radionuclides can be obtained only with a system of the resolution and sensitivity described here.

FRACTIONAL RELEASE, TRANSPORT, DEPOSITION, AND REDISTRIBUTION OF RADIOACTIVITY FROM PLOWSHARE CRATERING EVENTS

The broad objectives of this program are to document the total amount of radioactivity released by specific nuclear cratering events, particularly at the Nevada Test Site, and to study the transport, the deposition, and the redistribution of the debris. The solid state spectrometers described in the preceding section are used to quantitate the gamma emitting radionuclides. Studies at the Nevada Test Site are particularly emphasized in this program, which is expected to contribute strongly to the Bio-Medical Division's predictive effort by providing the necessary data for reliable checks of proposed theories and models.

This program is a broad, long-range one that began with the Schooner Event and will be repeated on several Plowshare events to establish good statistical data on the parameters of interest. We will make long-term air-activity measurements at times up to 1000 hours after detonation to record not only the primary distribution but also the secondary redistribution that occurs. These measurements bear directly on the question of how soon re-entry can be permitted for purposes of additional excavation following Plowshare events. We will also field very large-volume collectors to get large amounts of airborne debris for subsequent feeding experiments. The collection of large amounts of such material from the air rather than from the ground will remove many problems of contamination associated with such studies. In addition, we hope to cooperate with several investigators throughout the country who would be able (as part of their normal programs) to supply us with meaningful biological samples for the quantitation of radionuclide concentration. Analysis of such samples with our high-resolution counting facilities should yield valuable information on the transport of radionuclides after Plowshare cratering events.

Fractional Release

Our immediate objective after a cratering event is to determine the total radioactivity released into the environment. The most appropriate method is to measure the radioactivity within the cloud at early times. These measurements have been made in the past by aircraft sampling in conjunction with photographic techniques. The measurements made in this manner can be criticized because of the great variability of concentration within the cloud. The Lawrence Radiation Laboratory recently initiated a much improved method on Schooner: several hundred samplers suspended from parachutes were dropped through the cloud. Some of these drop-packages have sequential samplers and provide data on cloud concentration as a function of vertical height. The Bio-Medical Division actively participated by helping in the package design and by performing the gamma spectroscopy on the recovered filters. Thus data are being obtained on the isotopic fractionation of the cloud as a function of three dimensions as well as on the total activity contained in the cloud.

Transport

Information about the dispersal of the radioactive cloud as a function of extended time and distance is desirable. In Schooner, we participated in this area only by performing gamma spectroscopy on several filter samples supplied by the Nevada Aerial Tracking System of the Edgerton, Germeshausen and Greer Corporation. In the future we hope to extend these studies to cover more accurately conditions of cloud shear and to secure more extensive sampling. We will use whatever direct data are available, but our main effort will probably be to reconstruct transport phenomena from our own deposition data and those of other groups.

Deposition and Redistribution

The major purpose of this program is to study the deposition of debris at distances from a few thousand feet to several hundred miles. Eventually we hope to field about 100 stations to obtain samples of airborne debris and fallout material. The radionuclide content of these samples will be determined by gamma spectroscopy. By using programmed samplers to obtain both air and ground samplers as a function of time, we will study the dependency of deposition and fractionation on time and distance. With such data from several events, we will be able to assess the relationship between air and ground contamination.

One of the important practical questions for a variety of hoped-for applications of the Plowshare Program is how soon work crews may re-enter an area for additional excavation and other operations. Since some of our studies will continue for periods up to 1000 hours after the event, they should help provide answers to this question.

On the Schooner Event, we fielded 13 stations to collect air samples. These instruments were located at various points on the six- and fifty-mile arcs as well as at the sites of animal experiments. Each instrument consisted of a bank of six sequentially operated air pumps and high-efficiency convoluted air filters. An unique feature was a low-cost electronics system for sequential programming of the samplers either in a logarithmic or linear function. In addition, a sensitive radiation detector was developed that automatically turned on the samplers by detecting gamma rays, thus allowing unmanned operation at inaccessible locations. Figure 4 illustrates a typical station with the samplers six feet off the ground and the programmer and batteries beneath.

The several hundred samples obtained in this program are currently being analyzed for their content of gamma-emitting radionuclides by solid-state spectroscopy. These data will allow us to reconstruct the radionuclide concentration (pCi/m^3) as a function of time at several locations.

Preliminary data on one of the most prominent radionuclides, tungsten-181, are presented in Figure 5. Station T1, the hottest station on the 50-mile arc, was located near Tonopah, Nevada. Station S25 was located on the six-mile arc. Other data suggest that the hotline passed close to S25. Station S8 was located upwind from ground zero, and initial concentrations of radioactivity at this station were quite low.

Several points of interest are presented in Figure 5. At station T1 on the 50-mile arc, the peak concentration of tungsten-181 occurred 10 hours after detonation (integrated over six hours) and was 6400 pCi/m^3. At this time, the concentrations of tungsten-181 at stations S25 and T1 were equal, although T1 was 44 miles from S25. At station S25, very significant redistribution of debris was evident, and at 30 hours after detonation relatively large amounts of debris were still airborne.

In terms of re-entry, the data at S8 are perhaps the most interesting. This station was one mile upwind from ground zero, and although the initial concentrations of activity were low at 100 hours, this was the station that registered the greatest amount of activity. Again very significant redistribution of debris is indicated.

Figure 6 illustrates the early distribution of iodine-131 for stations S25 and S27 in the six-mile arc and for station T1 on the 50-mile arc. It is worth noting that at 10 hours after detonation the distributions were about equal and that at 40 hours significant redistribution had occurred at stations S25 and S27.

Figure 7 is a similar plot for tellurium-132. Again we note the equal concentrations of activity 10 hours after the shot at six and 50 miles and the redistribution 40 hours after the shot.

Several other radionuclides are being quantitated, and in addition data at later times will be similarly quantitated to study the effects of redistribution of radioactivity.

Sharpening of Predictive Ability

A rigorous attempt will be made to assemble the data obtained on the fractional release, transport, deposition and redeposition of radioactivity along with all other available data to gain a complete knowledge of the amount of activity released and its transport and impact upon man. In addition, these experimentally obtained values will be compared with those predicted by other programs in the Division. As a result, our ability to predict the consequences to man of a Plowshare detonation will be refined and sharpened from event to event.

THE ANALYSIS OF RADIOACTIVE PARTICLES PRODUCED IN PLOWSHARE CRATERING EVENTS

The major sources of radionuclides that enter the biosphere following nuclear events such as Plowshare detonations are the radioactive particles introduced into the atmosphere after the detonation. We have therefore established a Particle Analysis Program whose immediate objective was to obtain a complete quantitative description of the radioactive particle population produced by specific nuclear detonations. The long-range objective of the program was to determine how particle populations change as detonation conditions change, and thereby to establish a capability for predicting the characteristics of particle distribution from the specifications of detonation conditions. Success in achieving these objectives would provide essential information on the possible occurrence of "hot spots" following nuclear events.

The radioactive isotopes produced by nuclear detonations are distributed among the particle classes and particle sizes in a manner that varies from isotope to isotope and from detonation to detonation. Our studies on radioactive particles from the Plowshare Events Sedan, Palanquin, Cabriolet, Buggy, and Schooner indicate that the partitioning of the radionuclides produced by cratering detonations follows a pattern that can be understood in terms of a three-stage condensation process.

The first stage of condensation occurs in the underground cavity produced by the detonation. The refractory radionuclides, those whose boiling points are significantly higher than the melting temperature of the environmental soil, are quantitatively scavenged by the molten material that lines the cavity. Other radionuclides are incompletely scavenged in this stage. In the subsequent rupture, the molten cavity liner breaks up into particles that constitute a distinctive class, referred to here as slag particles. Both the radioisotopic composition and specific isotopic abundance in this particle appear to be relatively independent of particle size, indicating that the radionuclides in the slag particles are distributed within the particle volume.

The second stage of condensation occurs during the passage of the cavity gas through the strongly-shocked and crushed overlying rock or soil, up to the time of venting. During this stage the radioisotopes of intermediate volatility complete their condensation. However, since this crushed material is not melted, the radionuclides are surface-deposited rather than volume-deposited. The radioactive particles formed during this process are for the most part separated from the remaining radioactive gas at the time of venting and fall to the side to form the crater lip. This particle class will be referred to here as lateral ejecta.

The third stage of condensation occurs after venting. Only a small fraction of the crushed soil through which the radioactive gas has moved remains with the gas after venting occurs. Therefore, the highly volatile species are found to be significantly enriched in this soil fraction. The volatility of the individual radioisotopes may be inherent as in the case of gold or arsenic isotopes or it may be due to the isotope's having a rare gas precursor as in the case of fission-product barium or cesium isotopes. Again the condensation is on non-molten particles and consequently leads to surface deposition of the radionuclides. The particles in this class will be referred to here as vertical ejecta.

The partitioning of the radionuclide population among the particle categories can be determined from the fission yields in conjunction with several assumptions derived from the foregoing phenomenological description. These assumptions are that refractory radionuclides are in the main scavenged by the slag particles, that aerial filter samples of the radioactive cloud contain as their major components vertical ejecta and slag particles, and that close-in tray samples contain most of the lateral ejecta and slag particles. The partition values for typical refractory, volatile, and intermediate species for four cratering events are given in Table IV.

METABOLISM OF PLOWSHARE NUCLEAR DEBRIS IN PIGS, DOGS, AND GOATS

This program is concerned with the metabolism, including the biological availability, in large mammals of the radionuclides present in nuclear debris from Plowshare events. Studies of the biological availability of radionuclides in complex mixtures such as nuclear debris are essential since the data are often different and more meaningful than those obtained after feeding the radionuclide as a single chemical species. Accordingly, we have initiated feeding and inhalation studies of nuclear debris in pigs, dogs, and goats. Pigs (peccaries) were chosen because their gastrointestinal physiology closely resembles that of man and because pork is an important constituent of the diet, dogs (beagles) because their renal physiology closely resembles that of man, and goats because of their suitability for inhalation studies in the field.

In one part of this program, debris from specific Plowshare cratering events is administered orally to pigs and dogs. The animals are analyzed daily by whole-body counting for gamma ray-emitting radionuclides as are their urine and feces. At appropriate times, animals are sacrificed for specific organ analysis to determine the distribution of long-lived radionuclides. Wherever appropriate, beta-emitting radionuclides are quantitated in this and other Division programs after radiochemical separation and purification.

In other studies, pigs are placed in metabolic cages located on an arc within the predicted path of the radioactive cloud. Their feed is allowed to become contaminated by fallout, and is then fed daily for a week. The radionuclide contents of their organs, urine, and feces are then determined.

These experiments yield several kinds of information about the radionuclides: their identity and relative concentration in specific nuclear debris, their absorption across the intestinal wall, their body retention times, and the body distribution of long-lived radionuclides.

Figure 8 presents distribution data from an experiment in which debris was orally administered to a pig. The results obtained for antimony-122 are representative of data obtained for molybdenum-99, tellurium-132, gold-198, and tungsten-187, in which 10 to 30 percent of the ingested radionuclide was absorbed across the gut wall and excreted by the kidney. The remaining fraction was eliminated in the feces.

Figure 9 presents data on cerium-141 from the same experiment. Little or no cerium-141, lead-203, ruthenium-103, manganese-54, barium-140/lanthanum-140 from the debris was absorbed across the gut wall and excreted by the kidney. Most of these radionuclides were eliminated in the feces in the first two to three days. Figure 10 presents data on iodine-131, the only radionuclide absorbed to a large extent; 73 percent of the initial dose was excreted in the urine.

After eight days, antimony-122, tungsten-187 and lead-203 were no longer detectable by whole-body analysis. Two percent or less of molybdenum-99, cerium-131, tellurium-132, gold-198, manganese-54 and barium-140/lanthanum-140 was detectable. The only radionuclide remaining in appreciable amount after eights days was iodine-131, whose retention at that time was six percent of the administered dose.

Studies similar to these have now been completed in pigs and in dogs with debris from the same event and from different events. The metabolism of some of the radionuclides varies between animals and among events. In summary, our results indicate the importance of critically evaluating the biological availability of radionuclides produced in nuclear events.

The biological availability and the tissue distribution in goats of the gamma-ray-emitting radionuclides from a radioactive cloud were measured at the Nevada Test Site in conjunction with a cratering event. At each of three stations, all located three to 4.6 miles from ground zero, a lactating goat was stationed during the detonation in such a manner as to receive only the inhalable fraction of the radionuclides taken in by two air samplers. Thirty hours after the detonation, the goats were killed and their major organs were removed for quantitation of their gamma-emitting radionuclides. The nuclides molybdenum-99, iodine-132, iodine-131, ruthenium-103, antimony-122, tungsten-187 and barium-140/lanthanum-140 tended to be more readily absorbed across the lung; cesium-141, gold-198 and lead-203 were less readily absorbed. Most of the radionuclides were found in highest concentration in the upper lobe of the right lung. Table V presents data on the radionuclide content of some of the organs of the goat nearest the hot-line.

THE BIOLOGICAL AVAILABILITY OF DEBRIS RADIONUCLIDES IN THE DAIRY COW

The dairy cow represents an important link in the food chain to man by which not only radioiodine but many other radionuclides can enter his diet. In countries like ours, in which dairy products contribute a significant portion of the total diet, this may well be the major route of isotope transfer, particularly for infants and children. Consequently a program was instituted to determine the biological availability to the cow of radionuclides in nuclear debris.

This program involves work in several interrelated areas. The first is concerned with the biological availability of radionuclides in debris from nuclear events, the second with the biological availability of pure radionuclides, the third with environmental studies, and the fourth with _in vitro_ studies of radionuclide binding to plasma and milk proteins.

In a representative experiment on biological availability, a lactating cow was fed debris from a Plowshare cratering event. Figure 11 presents the data on the iodine-131 content in milk, plasma, urine and feces. Of the administered dose, 61 percent was excreted in the urine and seven percent was secreted in the milk. These data may be contrasted with comparable values of 14 percent for urine and two percent for milk for debris from an underground event that accidentally vented. They agree well, however, with data from an experiment in which sodium iodide labelled with iodine-131 was administered orally. In both debris experiments, the plasma-to-milk ratio for iodine-131 was unity after 72 hours, and thereafter the plasma levels exceeded those of milk, because iodine binding to plasma proteins prevented its excretion by the mammary gland or the kidney.

Figure 12 presents data on the relatively unavailable fission products barium-140/lanthanum-140. Figure 13 presents data on tungsten-181; about seven percent of the administered radiotungsten appeared in the urine and 0.5 percent in the milk. In the experiment described here, manganese-54, zirconium-95/niobium-95, cerium-141, neodymium-147 and lead-203 were not observed in milk, urine or plasma. Figure 14 presents a spectrum of the gamma-emitting radionuclides in the feces; solid state detectors have clearly quantitated manganese-54, zirconium-95/niobium-95, molybdenum-99, ruthenium-103, antimony-122, antimony-124, iodine-131, tellurium-131, tellurium-132, iodine-133, barium-140/lanthanum-140, cerium-141, neodymium-147, tungsten-181, tungsten-187, gold-198, lead-203 and others.

Table VI compares the recovery of orally administered radionuclides from several sources: two Plowshare cratering events, an underground accidental venting and commercially available pure radionuclides. Of particular interest are the data on iodine-131, which show a variation in the metabolic pattern from one kind of event to another.

In a study of maternal-fetal transfer, Plowshare debris, six weeks after the detonation, was administered to a near-term pregnant cow; a total of one kilogram was given in gelatin capsules, at a rate of 200 grams per day for five days. At 48 hours after the last administration, the cow was anesthetized and sacrificed. Tissue and blood samples were taken from both the fetus and the cow. Data from this experiment are summarized in Table VII. All values are compared to the cow plasma values normalized to unity, so as to point up the degree of concentration of specific radionuclides in specific tissues. The nuclide tungsten-181 appears to concentrate in maternal mammary gland, spleen, kidney, liver and bone and particularly in fetal bone. The last finding is in accord with other results from this Laboratory indicating that bone-plasma ratios as high as 200 or 300 to one can be reached in the bones of immature rats. The gold-198 seems to localize in the maternal kidney. The iodine-131 is concentrated in both the maternal and fetal thyroid; 4.5 percent of the administered dose was taken up by the maternal thyroid and 6.7 percent by the fetal thyroid. The concentration of iodine-131 per unit weight of wet tissue was twice as high in the fetal thyroid as in the maternal thyroid. The other radionuclides detected in the other studies were either absent or present only in very small amounts in some organs.

METABOLISM OF DEBRIS RADIONUCLIDES IN AQUATIC ANIMALS

The release of radionuclides in or near the hydrosphere results in their uptake by aquatic organisms in the food chain of man. At nuclear installations such as nuclear reactors of nuclear fuel production or processing plants, radionuclides are generally released at low regulated rates into established ecosystems. At the sites of nuclear detonations, large initial releases of radioactivity are followed by continuous long-term releases of small amounts leached from the initially deposited source.

Accordingly, a program was initiated to obtain information bearing on the problems of radioactive contamination of the hydrosphere from Plowshare and other nuclear events. It involves several different aspects: (1) assessment of the biological availability of radionuclides in nuclear debris, (2) evaluation of the biological turnover of critical elements in specific aquatic animals, (3) elemental analysis of aquatic organisms and their environmental water, and (4) investigation of the mechanisms of accumulation of specific elements.

The biological availability of radionuclides from nuclear debris is a function in great part of the matrix of the debris particles; and aquatic organisms can acquire radioactivity by ingesting radionuclides either in solution or in particulate matter. Therefore experiments were designed to study the influence of physical and chemical form on the availability. The source of the debris material was either contained underground events or fallout and crater lip material from cratering events. This particulate matter was separated into particle-size fractions which were then leached with various solutions to determine the distribution coefficients of the contained radionuclides; representative aquatic animals were then exposed to water that had circulated through the debris.

Table VIII presents distribution coefficients in synthetic seawater of debris radionuclides from a cratering event. The distribution coefficient is

$$K_d = \frac{F_s}{1 - F_s} \quad \frac{V}{W},$$

where F_s = the fraction of the total activity on the solid, $1 - F_s$ = the fraction of the total activity in the liquid, V = the volume of the liquid in milliliters equilibrated with W, and W = the weight of the material in grams. Comparable data are available for other radionuclides. Different distribution coefficients were obtained for many of the radionuclides in debris in an underground-contained event.

The biological availability of the debris radionuclides to specific aquatic animals has been evaluated in the past in the system shown in Figure 15. Typical data on representative marine and freshwater animals are presented in Tables IX and X. These data and data on other radionuclides show that a nuclide can be metabolized quite differently by different aquatic animals. We are presently determining biological availability in 2000-gallon aquaria in which the changes in the concentration of stable elements and radionuclides in the water, the sediments and the animals can be followed for extended periods of time. For proposed Plowshare excavations, we plan to study appropriate debris samples from past Plowshare tests in aquatic animals indigenous to the proposed sites.

Table XI presents concentration ratios of radionuclides in freshwater and marine animals after exposure to water circulated through debris from a cratering event.

We have also studied the biological turnover of certain radionuclides in bivalve and molluscs and other animals. Accumulation and loss of the nuclides were followed in the Laboratory under well-controlled conditions: constant concentrations of radionuclides and stable elements, controlled temperature, and specimens selected according to size. These parameters were then varied independently in order to identify the factors most critical in affecting biological turnover. Concentration factors and biological turnover were assessed simultaneously.

The elements most studied to date are zinc, manganese, cobalt, iron, europium, chromium, arsenic, cesium, and plutonium. From the results, we can conclude that the concentrations of some elements are not under homeostatic control, and that the animals contain pools of the elements with which the corresponding radionuclides are not readily equilibrated. They suggest further that anyone who proposes to use published concentration factors for predictive purposes should be aware of the precise conditions under which they were determined.

THE PERSISTENCE OF RADIONUCLIDES IN THE ECOSYSTEMS OF NUCLEAR DETONATION SITES

This program is concerned primarily with the behavior of long-lived radionuclides in the ecological and biological systems that reinvade nuclear detonation sites. The unique aspect of this research is the use of the detonation site as a natural laboratory in which real environmental parameters affect the movement of a radionuclide. Field studies were initiated in 1964 with a study of old detonation sites at Eniwetok Atoll in the Marshall Islands. The major emphasis was on tritium and carbon-14, two radionuclides that had not been looked for in the resurveys conducted by the University of Washington Laboratory of Radiation Biology. At the present, most of the radioecological research in this program is being conducted at the Nevada Test Site.

An example of the kind of research carried out at the sites of Plowshare excavations is our studies at Sedan Crater. I will particularly emphasize our studies on the fate of residual tritium because of its potential impact on the biosphere.

Approximately one million curies of residual tritium as THO was injected into the mass of earth deposited around the crater by the detonation. In 1966, we began studies at Sedan Crater on the behavior of this tritium in the soil (ejecta), the invading plant species, and the animal populations that subsist on the vegetation.

To study tritium distribution in an open ecological system, we first had to develop specialized analytical methods to extract the interstitial water from soils and the tissue or unbound water from plant samples and from the body water of mammals. These methods consist primarily of lyophilizing the material in glassware specially designed to collect the water from each sample. The resulting samples are assayed for tritium by liquid scintillation tehcniques. Tissue-bound tritium is determined in plant and animal tissues by a modified Schöniger method followed by liquid scintillation counting.

At Sedan Crater, we found essentially equilibrium concentrations in the soil water of the plant root zone, in the tissue water of the plant stems and leaves, and in the transpirational water released by the aerial portions of the plant. Tissue-water tritium concentrations in plants growing on Sedan ejecta are presented in Figure 16.

At the end of the annual growing season, the specific activity of tritium in the solid phase of the tissues of herbaceous plants such as the Russian thistle (Salsola kali) was almost equal to that found in the tissue water of the plant. These data are presented in Figure 17. This incorporation of tritium into the organic matter synthesized by plants growing on Sedan ejecta is mainly responsible for the tritium concentrations found in small mammals, reptiles, birds and even insects living in the Sedan area.

Some typical body-water tritium concentrations in mammals at Sedan Crater are presented in Figure 18. Tritium concentrations in the body water in the most abundant mammal at Sedan, the kangaroo rat (*Dipodomys merriami*), were more closely related to those of tissue bound tritium in plant tissue than they were to those of soil-water tritium, which vary seasonally at the depth of the burrows.

The effects of seasonal rainfall on the soil-water tritium profile in Sedan ejecta are readily observed in the data obtained by periodic sampling to depths of six feet (Figure 19). Both downward and upward soil-water movements are apparent; the pulse of winter rainfall, which lowers the tritium concentrations in the zero to three-foot stratum, is dissipated by evaporation and transpiration in the spring and summer.

A site inventory of tritium can be made by not only integrating the depth concentration profile, but also performing a second integration on the surface values to obtain the total areal inventory. These data indicated that five to six percent of the estimated original tritium inventory of the ejecta (crater lip to 1710 meters) was still present in the summer of 1968. This short half-residence time, in a region where the annual flux of environmental water is extremely small, seems to indicate that, despite persistently high concentrations of tritium in all ecosystem compartments, rather significant amounts are lost by the usual hydrological mechanisms of transpiration and evaporation, with some losses to a deeper soil-water compartment. Losses to the groundwater appear not to occur in this region; therefore soil-water and tritium dynamics are confined mostly to the surface stratum, probably no deeper than 10 feet.

The tritium concentrations in the small mammals at Sedan Crater constitute an unique kind of chronic exposure; this population of mammals apparently received its initial exposure to tritium *in utero* not only from body water but also from tritiated organic compounds received by placental transfer from the parent animal. Accordingly, they are being subjected to various kinds of physiological and biochemical studies. Preliminary data indicate that at the time of their capture the specific activity (disintegrations per minute of tritium per gram of hydrogen) of the tissues of Sedan kangaroo rats is significantly higher than that of their body water. In addition, certain changes, not yet precisely defined, are detectable in the structure and biochemical behavior of the DNA extracted from the livers of the Sedan kangaroo rats.

Our studies clearly indicate that tritium is the most abundant radionuclide in the postshot environment of Sedan. Figure 20 is an inventory of the major radionuclides at Sedan Crater. Residual tritium from this thermonuclear cratering detonation in the desert of Southern Nevada is present in all of the trophic levels of the natural ecosystem that has evolved in the postshot environment. These levels embrace not only the physical compartments of the soil substratum into which the tritium was injected or distributed by the detonation, but also the processes by which organic matter is synthesized in both plants and animals. When our studies on the DNA have been completed, we will have traced the environmental life history of a specific radionuclide from the substratum where it was deposited by a nuclear detonation to one of the most critical life compounds in the biological world.

SOMATIC EFFECTS OF LOW-DOSE RADIATION: CHROMOSOMES, RADIATION, HUMAN CANCER AND LEUKEMIA

No issue is more central to the nuclear age than the question of whether low doses of radiation delivered rapidly or over a very long period of time are harmful to man. Plowshare programs in particular are concerned with the possibilities that involve, or may involve, delivery, rapidly or slowly, of low total doses of ionizing radiation to a small segment of the human population.

It is important to develop some way to ascertain whether there is a threshold radiation dose below which no cancer or leukemia is produced in man, and, if there is no threshold, to define the dose-versus-effect curve in the region between zero and 10 rads and between zero and, say, 50 rads. The implications of a threshold or even of a non-linear variation of effect with dose are enormously important for Plowshare programs as well as for other uses of nuclear energy.

In the absence of reliable information concerning this issue, an approach believed to be conservative is used in calculating possible leukemia or cancer production from exposure to any release of radiation (external or from radionuclides internally). The approach used assumes a linear extrapolation from high-dose data; in essence it states that each rad of radiation increases the risk of cancer or leukemia by a certain amount, whether the total dose is one rad or 50 rads or 100 rads. It is believed that this assumption represents the worst possible case. Using such a conservative estimate, one can calculate that exposure of a very large population to a very small amount of radiation per person (for example, from a Plowshare event) can theoretically induce cancer or leukemia in a significant number of people.

Since it is unlikely that this question will be answered through studies of human populations, an experiment is therefore highly desirable. Such an experiment has two basic requirements: it must encompass radiation doses from approximately one rad or less upward to high doses, and the system under study must provide information relevant to the question of production of human cancer or leukemia by radiation.

Radiation is known to produce chromosome alterations in human and other cells; indeed, the production of such so-called chromosome aberrations has been measured quantitatively down to doses in the region of 10 to 20 rads. Within such studies, however, no method has ever been proposed for determining the relevance of observed chromosome damage to the production of important somatic effects of such radiation in humans or other intact mammals. The somatic effects of consequence are predominantly carcinogenesis, leukemogenesis, or other bases for life shortening. Only if the chromosome abnormalities cause cancer will such studies bear directly upon the question of whether low-dose radiation produces human cancer or leukemia.

The concept that abnormalities in chromosomes might be the cause of cancer was proposed by Theodor Boveri in 1902. If this is so, a specific abnormality or set of abnormalities should be unfailingly associated with cancer. The known effect of radiation on chromosomes, plus the Boveri concept of a chromosomal cause of cancer, suggested an approach that could provide relevant answers to the central question.

The point to be settled first is whether the concept that an appropriately imbalanced cell chromosome constitution, of whatever origin, would lead to a malignant tumor. Our approach to this question and its relation to low-dose radiation effects are in three successive phases:

1. Is there a specific single chromosome abnormality, or a specific set of abnormalities, in human cancer?

2. If there is, can radiation produce such abnormalities? This can be studied on human cells in culture rather than on humans.

3. If radiation can produce such abnormalities, is their production linear with dose down to low doses? Particularly, is there a true threshold dose?

For our experiments, electronic scanners and computer processing of the scan information were used, and faster, more accurate methods of preparing, observing, recording, and analyzing chromosome data were developed. Suitable cells were selected, and their individual chromosomes were measured and separated into groups by computer processing, with computer-programmed "cut-off" points for the group boundaries. A sufficient number of cells is measured so that the results are statistically significant with a high degree of confidence.

We are pleased to say that we have achieved the objective of developing a relevant study system for low-dose radiation in relation to human carcinogenesis and leukemogenesis. Our research indicates the existence of an invariant common to unlimited proliferation of human cells <u>in vitro</u> and to malignant growth in humans. This invariant is in the <u>form of a</u> marked excess of E-16 chromosomes, either absolute or relative to other classes of chromosomes. Our studies of 14 established human cell lines show that the E-16 chromosomal imbalance is present without exception and is strong in every case. We appear to be nearing the point where it is possible to say that E-16 chromosome imbalance is an invariant of established human cell lines. In addition, studies on 10 cases of human cancer, including both malignant effusions and several primary solid cancers, also demonstrate the E-16 chromosome imbalance.

Of great interest are our studies on the effects of viruses on human cells. Virus alteration of normal diploid human cells to established lines had, of course, been accomplished by other workers, using SV-40 virus and others. Indeed, at this time, of the three major known modalities of cancer induction (viruses, carcinogenic chemicals and radiation) only viruses have been unequivocally able to alter diploid cells to established human cell lines. We have studied human cells that had been converted into a permanent line with SV-40 virus. Chromosome studies of these cells show that SV-40 virus-altered cells show the same E-16 chromosome imbalance previously demonstrated by us for spontaneously established human cell lines and for human cancers (effusions or solid tumors) studied directly. Thus a known oncogenic virus produces the E-16 chromosome imbalance in the course of *in vitro* alteration of diploid human cells to altered cells with malignant proliferative properties.

The major objectives ahead are:

1. Ascertainment of whether or not E-16 chromosome imbalance *determines* malignant behavior of cells thus imbalanced.

2. Ascertainment of whether or not radiation can imbalance human diploid cells in culture with respect to E-16 content and concomitantly transform such cells into established cell lines. Such studies are underway at present. Wholly irrespective of the E-16 chromosome issue, the question of whether or not *established cell line production* is possible with radiation alone is one of the most central importance in the entire area of the somatic effects of radiation.

SELECTED PUBLICATIONS OF THE BIO-MEDICAL DIVISION OF PARTICULAR RELEVANCE TO PLOWSHARE EVENTS

Anspaugh, Lynn R., Special Problems of Thyroid Dosimetry: Considerations of I^{131} Dose as a Function of Gross Size and Inhomogeneous Distribution, UCRL-12492, Lawrence Radiation Laboratory, Livermore (March 25, 1965).

Anspaugh, Lynn R., John W. Gofman, Ora A. Lowe and Walter H. Martin, X-ray Fluorescence Analysis Applied to Biological Problems. In Proceedings of 2nd Symposium on Low Energy X- and Gamma Sources and Applications (March 1967) p. 315.

Anspaugh, Lynn R. and William L. Robison, Quantitative Evaluation of the Biological Hazards of Radiation Associated with Project Ketch, UCID-15325, Lawrence Radiation Laboratory, Livermore (May 8, 1968).

Burton, C. Ann and Michael W. Pratt, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. III. Biological Guidelines for Device Design, UCRL-50163 (Pt. III Rev. 1), Lawrence Radiation Laboratory, Livermore (1968).

Chapman, William H., The Changing Frequency of Thyroid Carcinoma and Hashimoto's Thyroiditis as Related to Diagnostic Criteria, Iodized Salt and Radiation, UCRL-50376, Lawrence Radiation Laboratory, Livermore (1968).

Chapman, William H., H. Leonard Fisher and Michael W. Pratt, Concentration Factors of Chemical Elements in Edible Aquatic Organisms, UCRL-50564, Lawrence Radiation Laboratory, Livermore (1968).

Chertok, Robert and Suzanne Lake, The Availability in the Peccary Pig of Nuclear Debris from the Plowshare Excavation, Buggy. (In preparation)

Chertok, Robert and Suzanne Lake, A Field Study of the Availability in the Domestic Pig of Nuclear Debris from the Plowshare Excavation, Schooner. (In preparation)

Cranston, Fred P. and Lynn R. Anspaugh, Preliminary Studies in Nondispersive X-ray Fluorescent Analysis of Biological Materials, UCRL-50569, Lawrence Radiation Laboratory, Livermore (January 6, 1969).

Fisher, H. Leonard, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. VI. Transport of Nuclear Debris by Surface and Groundwater, UCRL-50163 (Part VI), Lawrence Radiation Laboratory, Livermore. (In preparation)

Geesaman, Donald P., A Study of the Effects of Insoluble Alpha-Emitting Aerosols on Deep Respiratory Tissue, UCRL-50387, Lawrence Radiation Laboratory, Livermore (1968).

Gofman, John W., The Hazards to Man from Radioactivity. In Engineering with Nuclear Explosives (Proceedings of the Third Plowshare Symposium, University of California, Davis, April 21, 1964), TID-7695 (1964).

Gofman, John W., J. L. Minkler and R. K. Tandy, A Specific Common Chromosomal Pathway for the Origin of Human Malignancy, UCRL-50356, Lawrence Radiation Laboratory, Livermore (Nov. 20, 1967).

Harrison, Florence L., Accumulation and Distribution of Mn^{54} and Zn^{65} in Freshwater Clams. Proc. 2nd Natl. Symp. of Radioecology, Ann Arbor, Mich., AEC, ESA, and Univ. of Mich., May 15-17, 1967, in press.

Harrison, Florence L., Concentration Factors - Their Use and Abuse, UCRL-50347, Lawrence Radiation Laboratory, Livermore (Nov. 7, 1967).

Harrison, Florence L., Physical and Chemical Characteristics and Biological Availability of Debris from Underground Nuclear Detonations, UCRL-50596 (in press).

Harrison, Florence L. and Dorothy J. Quinn, Short-Term Studies on the Accumulation and Distribution of ^{46}Sc, ^{51}Cr, ^{59}Fe, ^{60}Co and ^{155}Eu in *Anodonta nuttalliana* Lea, UCRL-71607, to be submitted to Health Physics.

Hatch, F. T., J. A. Mazrimas, G. G. Greenway, J J. Koranda and J. L. Moore, Studies on Liver DNA in Tritiated Kangaroo Rats Living at Sedan Crater, UCRL-50461, Lawrence Radiation Laboratory, Livermore (1968).

Heft, Robert E. and William A. Steele, Procedures for the Systematic Separation and Analysis of Radioactive Particles from Nuclear Detonations, UCRL-50428, Lawrence Radiation Laboratory, Livermore (May 17, 1968).

Heft, Robert E., The Characterization of Radioactive Particles from Nuclear Weapons Tests. Advances in Chemistry, in press.

Koranda, John J., Preliminary Studies of the Persistence of Tritium and Carbon-14 in the Pacific Proving Ground. Health Physics 11, 1445 (1965).

Koranda, John J., Agricultural Factors Affecting the Daily Intake of Fresh Fallout by Dairy Cows, UCRL-12479, Lawrence Radiation Laboratory, Livermore (March 19, 1965).

Koranda, John J., Residual Tritium at Sedan Crater. Proc. 2nd Natl. Symp. on Radioecology, Ann Arbor, Mich., May 15-17, 1967 (in press).

Koranda, John J., J. R. Martin and R. W. Wikkerink, Residual Tritium at Sedan Crater. Part II. Soil and Ejecta Studies. UCRL-50360, Lawrence Radiation Laboratory, Livermore (Dec. 7, 1967).

Koranda, John J., J. R. Martin and R. Wikkerink, Leaching of Radionuclides at Sedan Crater. Advances in Chemistry (in press).

Ng, Yook C., C. Ann Burton and Stanley E. Thompson, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. IV. Handbook for Estimating the Maximum Internal Dose from the Deposition of Radionuclides Released to the Biosphere. UCRL-50163 (Pt. IV), Lawrence Radiation Laboratory, Livermore (1968).

Ng, Yook C., C. Ann Burton and Stanley E. Thompson, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. IV. Handbook for Estimating the Maximum Internal Dose from Radionuclides Released to the Biosphere, UCRL-50163 (Pt. IV ADD. I), Lawrence Radiation Laboratory, Livermore (1968).

Phelps, Paul L., Keith O. Hamby, Bernard Shore and Gilbert D. Potter, Ge(Li) Gamma-Ray Spectrometers of High Sensitivity and Resolution for Biological and Environmental Counting, UCRL-50437, Lawrence Radiation Laboratory, Livermore (May 24, 1968).

Potter, G. D., David R. McIntyre and Deborah Pomeroy, Transport of Fallout Radionuclides in the Grass to Milk Food Chain Studied with a Germanium Lithium-Drifted Detector. Health Physics 16, 297 (1969).

Potter, Gilbert D., Deborah Pomeroy and David R. McIntyre, Residual Gamma-Emitting Radionuclides in Nevada Range Cattle as Observed with a Lithium-Drifted Germanium Detector, UCRL-70812 (1967).

Potter, Gilbert D., David R. McIntyre and Gerald M. Vattuone, Biological Availability of Radionuclides from an Accidental Nuclear Venting in the Dairy Cow. (In preparation)

Potter, Gilbert D., David R. McIntyre and Gerald M. Vattuone, Biological Availability of Radionuclides in the Dairy Cow from Cabriolet (a Plowshare nuclear cratering event). (In preparation)

Potter, Gilbert D., Gerald M. Vattuone and David R. McIntyre, Maternal-Fetal Transfer of Orally Administered Radionuclides from Buggy (a Plowshare nuclear cratering event). (In preparation)

Potter, Gilbert D., Gerald M. Vattuone and David R. McIntyre, Biological Availability of Radionuclides from Schooner in the Dairy Cow. (In preparation)

Saunders, E. W. and C. J. Maxwell, Paralleling Planar Ge(Li) Detectors for Counting Large Volume Biological Samples, IEEE Transactions on Nuclear Science NS-15 No. 1, 423 (1968).

Stone, Stuart P., Chromosome Scanning Program at LRL. Part I. Chromo, a Set of Chromosome Pattern-Recognition Programs, UCRL-50364 Part I, Lawrence Radiation Laboratory, Livermore (Nov. 25, 1967).

Tamplin, Arthur R., Iodine-131, Iodine-133 and Cow Milk, UCRL-14146, Lawrence Radiation Laboratory, Livermore (1965).

Tamplin, Arthur R., Discussion on "Thyroid Irradiation in Utah Infants Exposed to Iodine-131." Scientist and Citizen 8 (9), 3 (1966).

Tamplin, Arthur R., Estimation of Dosage to Thyroids of Children in the U.S. from Nuclear Tests Conducted in Nevada During 1952 and 1955, UCRL-70787 (November 1967).

Tamplin, Arthur R., Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. I. Estimation on the Maximum Contamination of Agricultural Land. UCRL-50163 (Part I), Lawrence Radiation Laboratory, Livermore (1967).

Tamplin, Arthur, R., H. Leonard Fisher and William H. Chapman, Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices. V. Estimation of the Maximum Dose from Internal Emitters in Aquatic Food Supply. UCRL-50163 (Pt. V), Lawrence Radiation Laboratory, Livermore (1968).

TABLE I

ESTIMATED MAXIMUM DOSAGE[a] VIA MILK TO THE CHILD'S WHOLE BODY AND BONE FROM ^{239}PU FISSION PRODUCTS

Radionuclide	Whole Body (rad/kt)	Bone (rad/kt)
^{131}I	0.31	0.16
^{136}Cs	0.26	0.26
^{111}Ag	0.19	0.12
^{133}I	0.14	0.11
^{99}Mo	0.098	0.14
^{89}Sr	0.080	0.60
^{137}Cs	0.065	0.065
^{90}Sr	0.053	0.45
^{140}Ba	0.010	0.083
^{132}Te	0.009	0.010
Total	1.2	2.0

[a] As a consequence of wet deposition by rainout at 12 hours after detonation.

TABLE II

ESTIMATED MAXIMUM DOSAGE[a] VIA MILK TO THE CHILD'S WHOLE BODY AND BONE FROM ACTIVATION PRODUCTS PRODUCED IN GRANITE

Radionuclide	Whole Body (rad/mole)	Bone (rad/mole)
^{24}Na	2.7	2.7
^{32}P	0.038	0.22
^{86}Rb	0.038	0.038
^{84}Rb	0.028	0.028
^{42}K	0.019	0.019
^{134}Cs	0.009	0.009
^{22}Na	0.004	0.004
^{45}Ca	0.003	0.031
^{82}Br	0.001	0.001
Total	2.8	3.1

[a] As a consequence of wet deposition by rainout at 12 hours after detonation.

TABLE III

ESTIMATED AND MEASURED CONCENTRATION OF RADIONUCLIDES IN GRASS AND MILK

Radionuclide	Forage (pCi/kg)		Milk (pCi/kg)	
	Estimated	Measured[a]	Estimated	Measured[a]
^{131}I	5000	5000	1000	930
^{137}Cs	19	43	3	2
^{99}Mo	1110	1050	82	20
^{140}Ba	5550	5740	33	71[b]
^{132}Te	900	1510	9	7

[a] Potter, G. et al., "Biological Availability of Radionuclides in Fallout from the Chinese Nuclear Test of December 1966," Lawrence Radiation Laboratory, Livermore, Rept. UCRL-70301 (1966).

[b] Determined as $^{140}Ba/^{140}La$.

TABLE IV

RADIONUCLIDE DISTRIBUTION VALUES FROM CRATERING EVENTS

	Fraction of nuclide in:			
	Slag	Lateral ejecta	Vertical ejecta	Cratering event
^{144}Ce	1.00			All events
^{132}Te	0.393	0.553	0.054	A
^{137}Cs	0.133	0.442	0.425	A
^{106}Ru	0.264	0.063	0.673	B
^{137}Cs	0.060	0.015	0.925	B
^{141}Ce	0.922	0.074	0.004	C
^{137}Cs	0.103	0.474	0.423	C
^{141}Ce	0.695	0.302	0.003	D
^{137}Cs	0.100	0.590	0.310	D
^{131}I	0.538	0.457	0.005	D
^{181}W	0.715	0.283	0.002	D

TABLE V

RADIONUCLIDE CONTENT (pCi/kg) OF ORGANS OF GOAT WHICH RECEIVED INHALABLE FRACTION OF RADIONUCLIDES FROM CRATERING EVENT

	^{99}Mo	^{141}Ce	^{132}Te	^{203}Pb	^{131}I	^{198}Au	^{103}Ru	^{122}Sb	^{187}W	^{140}Ba/^{140}La
Mammary Gland	30	5	90	25	570	20	ND[a]	45	400	55
Milk	15	3	70	25	1190	40	1	30		80
Thyroid	485	ND	1850	2560	62830	570	ND	950	20160	ND
Ovary	ND	257	2060	110	ND	ND	ND	2470		1130
Fat	ND	32	73		260		30	ND		350
Filter[b]	0.13	0.1	1.5	2.2	0.50	0.2	0.11	1.0	12.4	1.3

[a] ND (not detectable)

[b] picocuries per liter

TABLE VI

RECOVERY OF ORALLY ADMINISTERED RADIONUCLIDES FROM THE DAIRY COW

Nuclide	Event or chemical form	Percent of administered dose in: Feces	Urine	Milk
^{54}Mn	PC I[a]	110	ND[d]	ND
	PC II[a]	83	ND	ND
	$MnCl_2$[c]	85	$< 10^{-3}$	$< 10^{-3}$
^{74}As	PC II	49	29	0.002
	Na_3AsO_4	45	20	0.1
^{88}Y	PC II	104	2	ND
	YCl_3	88	ND	ND
^{95}Zr	PC I	76	ND	ND
	Zr oxalate	98	$< 10^{-3}$	$< 10^{-5}$
^{99}Mo	PC I	80	2	0.2
	UGV[b]	82	8	1
	$(NH_4)_2MoO_4$	104	10	2
^{103}Ru	PC I	109	ND	ND
	PC II	101	8	ND
	$RuCl_3$	93	0.2	10^{-3}
^{122}Sb	PC I	105	0.2	ND
^{124}Sb	$SbCl_3$	114	1	0.02
^{131}I	PC I	42	61	7

TABLE VI (continued)

Nuclide	Event or chemical form	Percent of administered dose in:		
		Feces	Urine	Milk
^{131}I	PC II	45	36	2
	UGV	82	14	3
	NaI	16	60	7
^{132}Te	PC I	114	2	0.1
	PC II	97	2	0.8
	Na_2TeO_3	112	2	0.6
^{133}I	UGV	68	14	3
$^{140}Ba/^{140}La$	PC I	112	0.4	0.2
	PC II	107	0.1	0.1
^{141}Ce	PC I	112	ND	ND
	$Ce(NO_3)_4$	83	0.4	0.1
^{147}Nd	PC I	71	ND	ND
	$NdCl_3$	88	0.02	0.01
^{181}W	PC I	94	7	0.1
^{187}W	PC I	80	9	0.5
	PC *II*	100	11	0.2
	Na_2WO_4	70	3	0.3
^{196}Au	PC I	112	0.2	0.1
^{203}Pb	PC I	76	ND	ND

[a] Plowshare cratering event.

[b] Underground accidental venting.

[c] Chemical formulas denote commercially available pure radionuclides.

[d] Not detected.

TABLE VII

TISSUE/PLASMA RATIOS† OF MATERNAL AND FETAL TISSUES FROM A PREGNANT COW FED DEBRIS FROM PLOWSHARE NUCLEAR CRATERING EVENT

Sample	^{181}W	^{196}Au	^{131}I	^{103}Ru	^{124}Sb	^{137}Cs	^{140}Ba	^{40}K
Maternal plasma	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maternal spleen	1.56*	0.52	0.19	ND	25.3*	169.0*	.50	2.90*
Maternal pancreas	0.37	0.18	0.21	ND	4.2*	230.0*	1.06*	4.55*
Maternal mammary	1.40*	0.45	0.51	1.1*	4.4*	115.0*	16.5*	2.25*
Maternal bile	0.003	0.12	0.61	3.7*	49.0*	2,840.0*	1.3*	1.10*
Maternal placenta	0.62	0.40	0.69	ND	ND	340.0*	3.0*	3.30*
Amniotic fluid	0.35	ND	0.31	ND	21.6*	9.6*	0.2	0.26*
Maternal kidney	8.60*	10.09*	0.45	9.8*	88.0*	423.0*	8.10*	3.56*
Fetal kidney	0.26	0.06	1.26*	ND	4.7*	128.0*	0.12	4.20*
Maternal thyroid	0.60	ND	5,450.0*	ND	ND	ND	ND	ND
Fetal thyroid	0.005	ND	10,500.0*	ND	ND	ND	ND	ND
Maternal muscle	0.094	0.04	0.05	ND	3.0*	111.0*	0.21	4.27*
Fetal muscle	0.026	0.03	0.05	2.2*	3.4*	71.0*	0.16	3.87*
Maternal liver	3.14*	0.93	0.32	ND	ND	200.0*	0.44	2.14*
Fetal liver	0.033	0.025	1.27*	ND	ND	118.0*	ND	2.38*
Maternal blood	0.05	0.83	0.67	ND	3.8*	26.0*	1.0	3.20*
Fetal blood	0.069	ND	1.97*	2.8*	ND	27.0*	ND	4.50*
Maternal RBC	0.096	0.68	0.12	ND	8.0*	37.8*	0.29	4.55*
Maternal bone	1.41*	0.60	0.10	ND	ND	34.0*	55.0*	ND
Fetal bone	21.2*	ND	0.67	ND	ND	45.5*	113.0*	5.70*
Fetal cartilage	12.8*	ND	0.66	ND	ND	30.0*	91.0*	3.80*
Maternal marrow	0.19	ND	ND	3.5*	ND	33.0*	4.30*	9.64*
Fetal marrow	1.14*	ND	0.87	6.1*	ND	27.4*	76.0*	2.32*
Total pCi in Admin. dose	2.07×10^{10}	2.6×10^{8}	2.79×10^{9}	2.76×10^{8}	ND	ND	6.38×10^{8}	ND
pCi/100 g Mat. plasma	8.46×10^{3}	9.37×10^{2}	1.21×10^{5}	1.33×10^{2}	2.3	0.05	1.33×10^{2}	99.0

† pCi in 100 g tissue/pCi in 100 g maternal plasma (wet weight)

* Tissues with tissue/maternal plasma ratio >1.0

ND = Not detected

TABLE VIII

DISTRIBUTION COEFFICIENTS IN SYNTHETIC SEA WATER OF DEBRIS RADIONUCLIDES FROM A CRATERING EVENT

Radionuclide	Size of particles in fraction			
	> 1000 < 4000 μ	> 250 < 1000 μ	> 62 < 250 μ	< 62 μ
^{54}Mn	3,400	4,900	4,100	2,500
^{58}Co	4,500[a]	15,000[a]	6,500[a]	180[a]
^{59}Fe	ND[b]	ND[b]	ND[b]	ND[b]
^{103}Ru	4,900	2,900	1,000	1,400
^{124}Sb	520	160	74	83
^{140}Ba/^{140}La	260[a]	52[a]	19[a]	40[a]
^{141}Ce	47,000[a]	3,100[a]	2,400[a]	8,200[a]

[a] *Fractional standard deviation of data > 0.20.*

[b] Not detected.

TABLE IX

RADIONUCLIDE CONCENTRATIONS IN TISSUES OF MARINE ANIMALS EXPOSED TO SEA WATER CIRCULATED THROUGH DEBRIS FROM A CRATERING EVENT

Animal and Tissue	Days of Exposure	^{54}Mn	^{103}Ru	^{124}Sb	^{131}I	^{140}Ba/^{140}La	^{141}Ce
Fish, whole body (Gobiosoma bosci)	6	270[b]	2,200	7,100	320,000	290,000	c
Clam, edible portions (saxidomis giganteus)	20	960[b]	1,700	520[b]	16,000	16,000[b]	1,100[b]
Crab, muscle (Cancer productus)	20	1,800[b]	1,400	2,300[b]	210,000	310,000	1,400[b]
Crab, viscera	20	1,700[b]	14,000	11,000	9,500,000	2,100,000	690,000[b]
Sea Water							
Day 6		280[b]	2,900	6,600	4,500	220,000	110
Day 20		470[b]	3,900	13,000	31,000	230,000	250

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[a] Corrected for decay to time of detonation of event.

[b] Fractional standard deviation of data > 0.20.

[c] Low level, not quantitated.

TABLE X

RADIONUCLIDE CONCENTRATIONS IN TISSUES OF FRESHWATER ANIMALS EXPOSED TO POND WATER CIRCULATED THROUGH DEBRIS FROM A CRATERING EVENT

Animal and Tissue	Days of Exposure	Radionuclide Concentration[a] pCi/kg					
		^{54}Mn	^{103}Ru	^{124}Sb	^{131}I	^{140}Ba/^{140}La	^{141}Ce
Fish, muscle (Carassius auratus)	7	b	4,100[c]	b	b	b	620
Fish, viscera and skeleton (Carassius auratus)	7	b	2,400	6,100	230,000	360,000	2,100
Clam, edible portions (Anadonta nuttalliana)	21	440[c]	6,200	15,000	150,000[c]	180,000	b
Crayfish, muscle (Astacus sp.)	21	b	b	b	b	47,000[c]	3,500[c]
Crayfish, viscera (Astacus sp.)	21	6,000	39,000	12,000[c]	4,300,000	4,600,000	16,000
Pond Water							
Day 6		830	3,100	3,600	28,000	110,000	620
Day 20		ND[d]	5,300	8,800	84,000	150,000	ND[d]

[a] Corrected for decay to time of detonation of the event.

[b] Low level, not quantitated.

[c] Fractional standard deviation of data > 0.20.

[d] ND (not detectable)

TABLE XI

CONCENTRATION RATIOS OBSERVED IN FRESHWATER AND MARINE ANIMALS EXPOSED TO WATER CIRCULATED THROUGH DEBRIS FROM A CRATERING EVENT

Animal and Tissue		Days of Exposure	Concentration ratios:					
			^{54}Mn	^{103}Ru	^{124}Sb	^{131}I	^{140}Ba/^{140}La	^{141}Ce
Fish, whole body	FW	7	a	0.8	2	8	3	3
	SW	6	1[b]	0.8	1[b]	7	1.3	a
Clam, edible part	FW	21	440[b] ND[c]	1.2	2	2[b]	1.3	a
	SW	20	2[b]	0.4[b]	0.1[b]	0.5	0.1[b]	4[b]
Crustacean, muscle	FW	21	a	a	a	a	0.3[b]	3,500[b] ND[c]
	SW	20	4[b]	0.4	0.2[b]	7	1.3	6[b]
Crustacean, viscera	FW	21	6,000 ND[c]	7	1.3[b]	51	31	16,000 ND[c]
	SW	20	4[b]	4	0.9	300	9	2,800[b]

[a] Low level, not quantitated.

[b] Fractional standard deviation > 0.20.

[c] Not detected

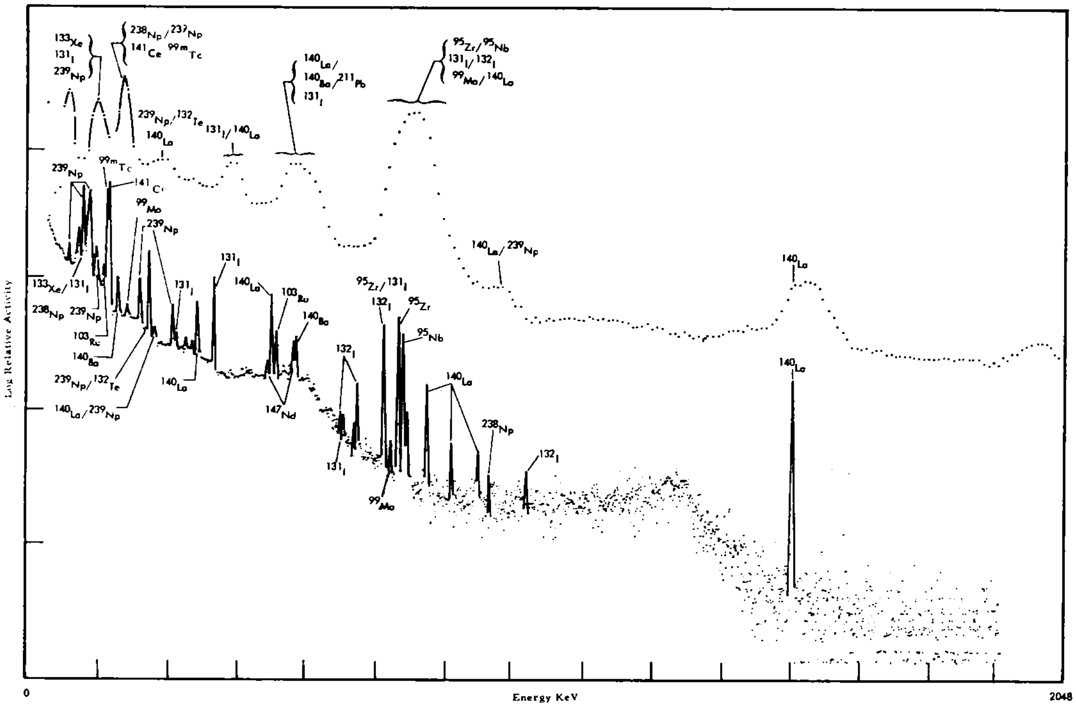

Figure 1. Comparison of two spectra from the same air-filter sample (presumed Chinese test). Upper spectra obtained with a 4 x 4 in. NaI (Tl) scintillation system. Lower spectrum obtained with our 8-cm^3 planar Ge(Li) detector.

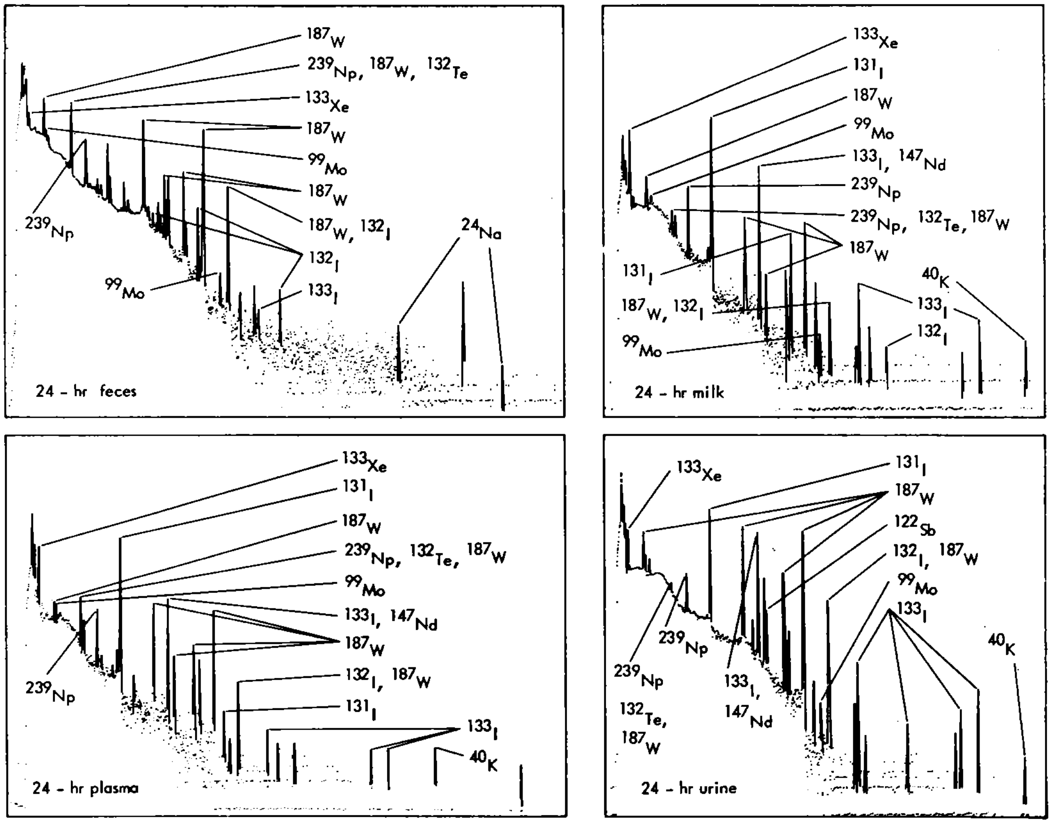

Figure 2. Gamma-ray spectra from various biological materials from a dairy cow that had been previously fed radioactive debris collected at the site of a nuclear detonation.

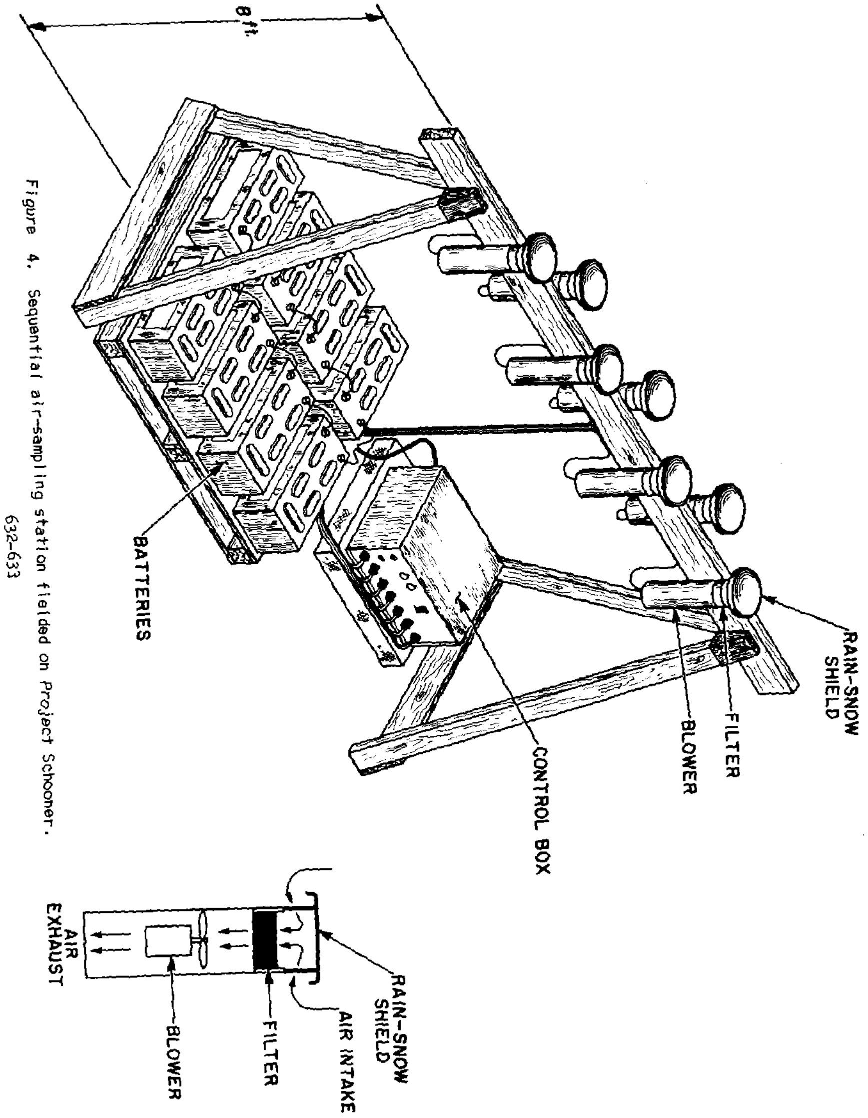

Figure 4. Sequential air-sampling station fielded on *Project Schooner*.

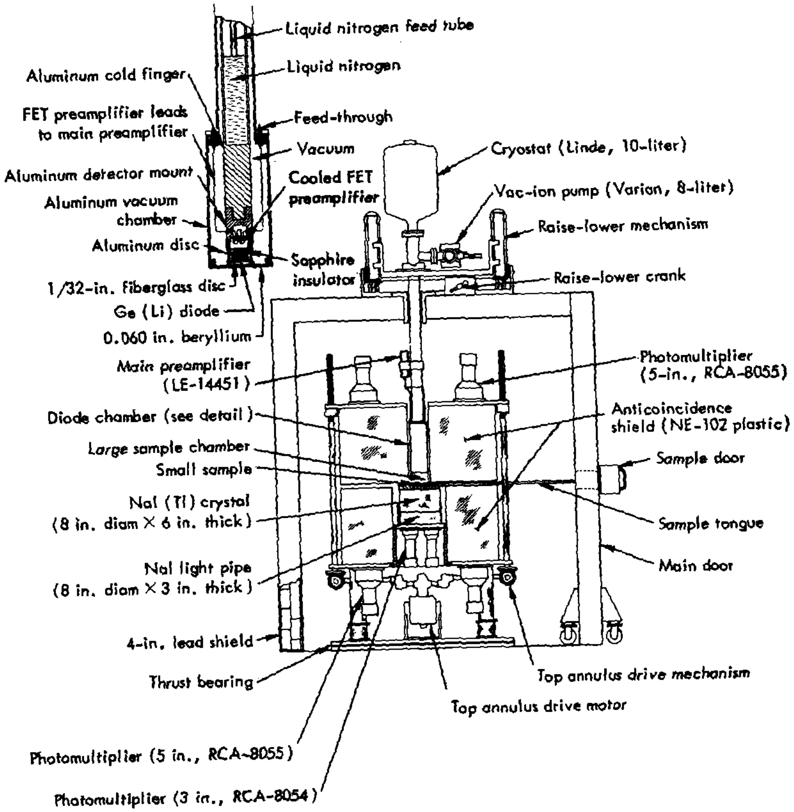

Figure 3. A schematic drawing of the gamma-ray spectrometer used in the Bio-Medical Division. The details of the Ge(Li) chamber and cooled FET preamplifier are given in the upper left corner.

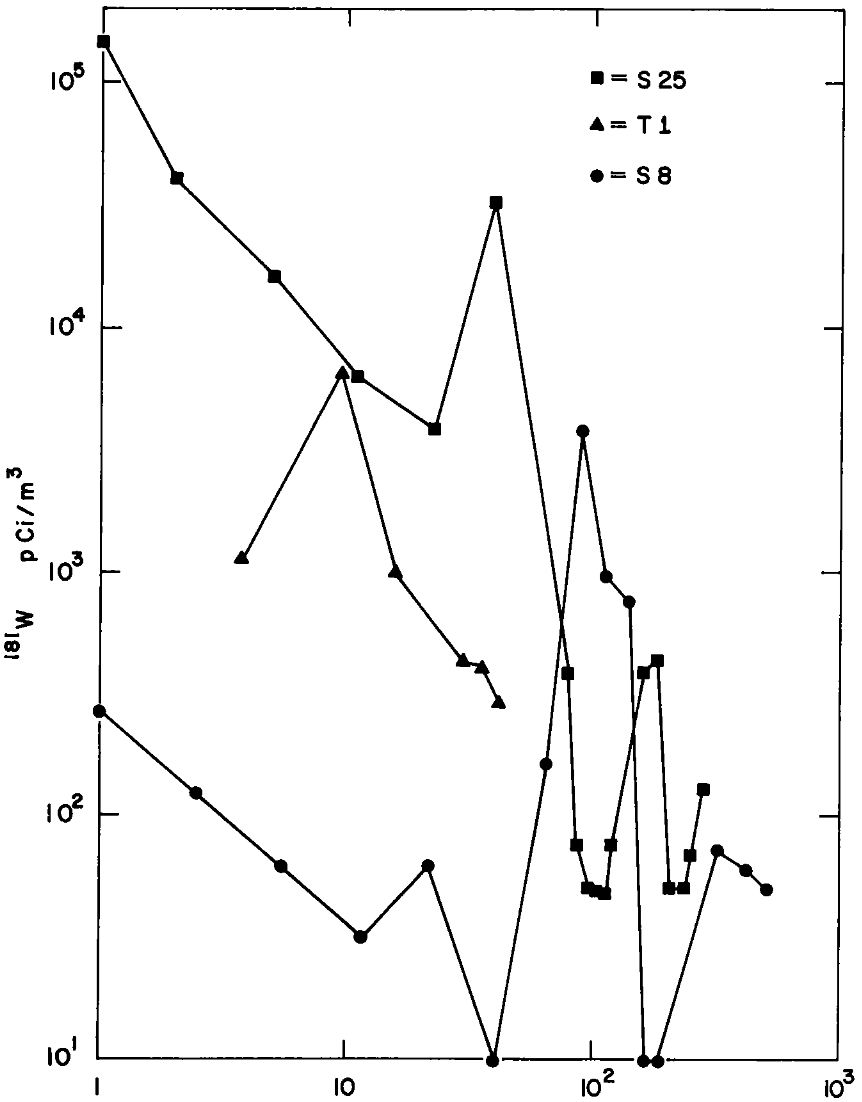

Figure 5. Air concentration of tungsten-181 as a function of time observed after Project Schooner.

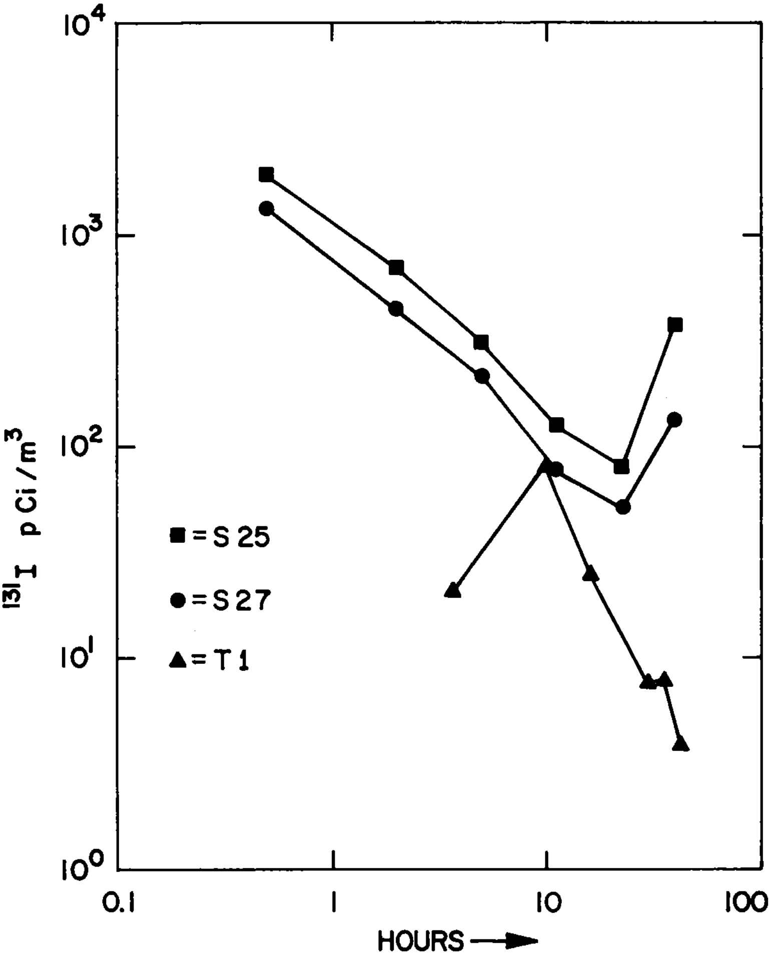

Figure 6. Air concentration of Iodine-131 as a function of time observed after Project Schooner.

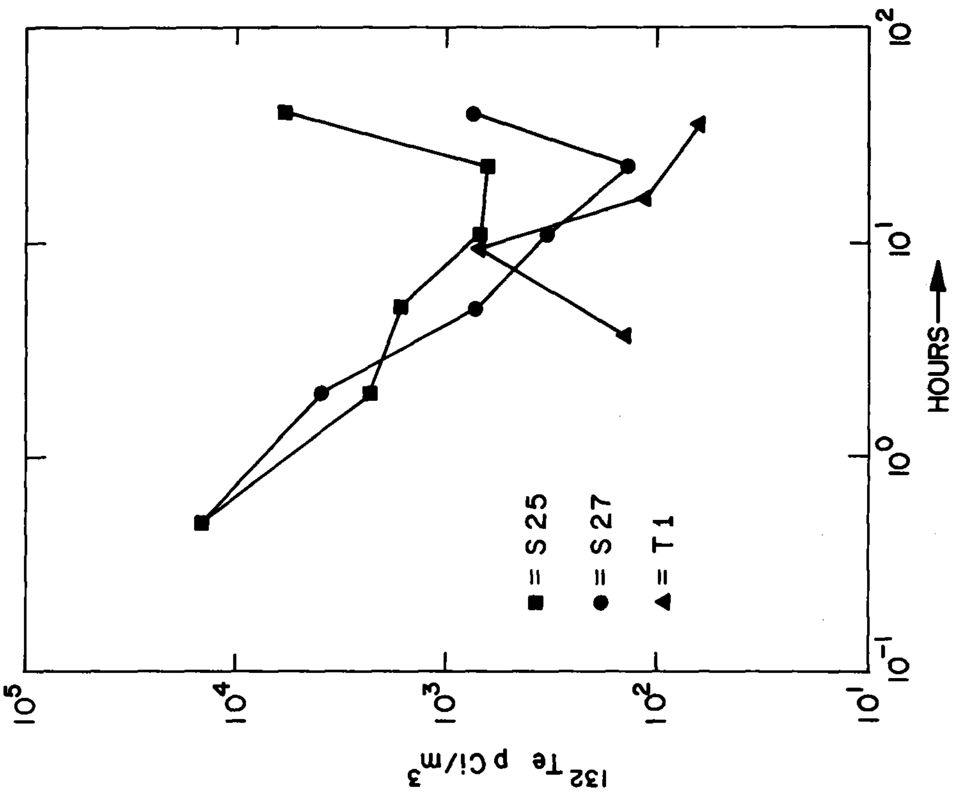

Figure 7. Air concentration of tellurium-132 as a function of time observed after Project Schooner.

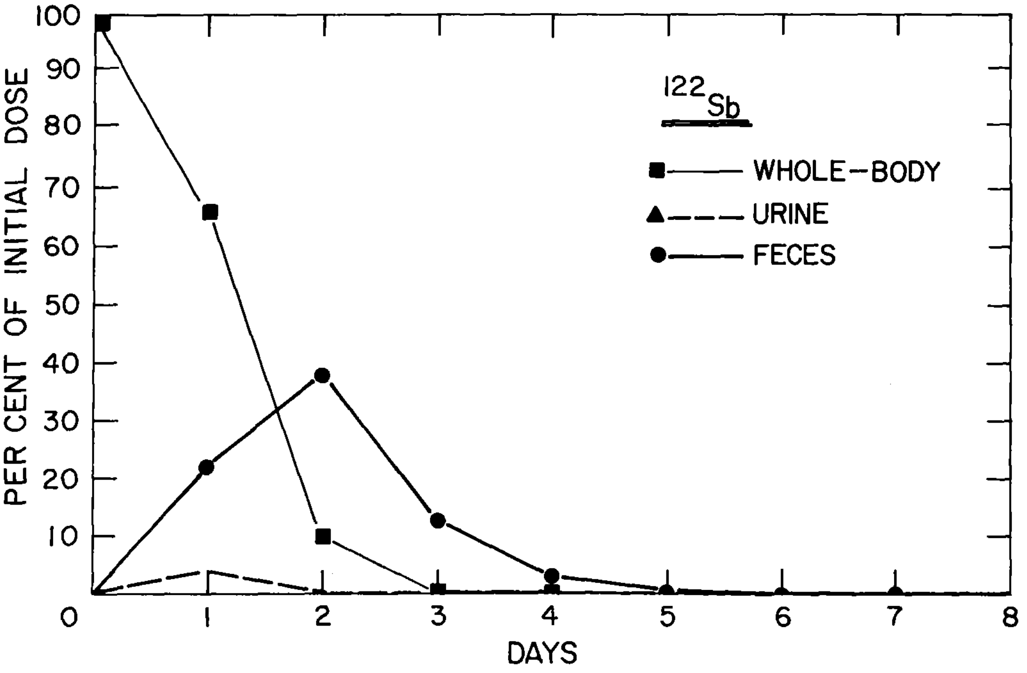

Figure 8. Uptake, retention and excretion in pig of antimony-122 from debris from Plowshare cratering event that was orally administered to the animal.

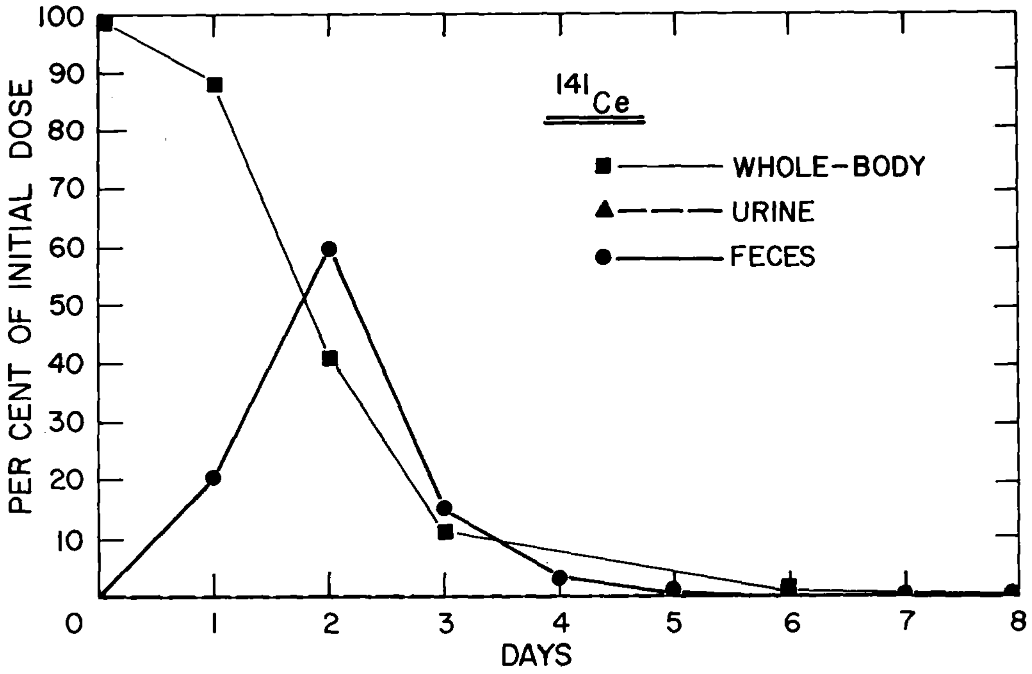

Figure 9. Uptake, retention and excretion in pig of cerium-141 from debris from Plowshare cratering event that was orally administered to the animal.

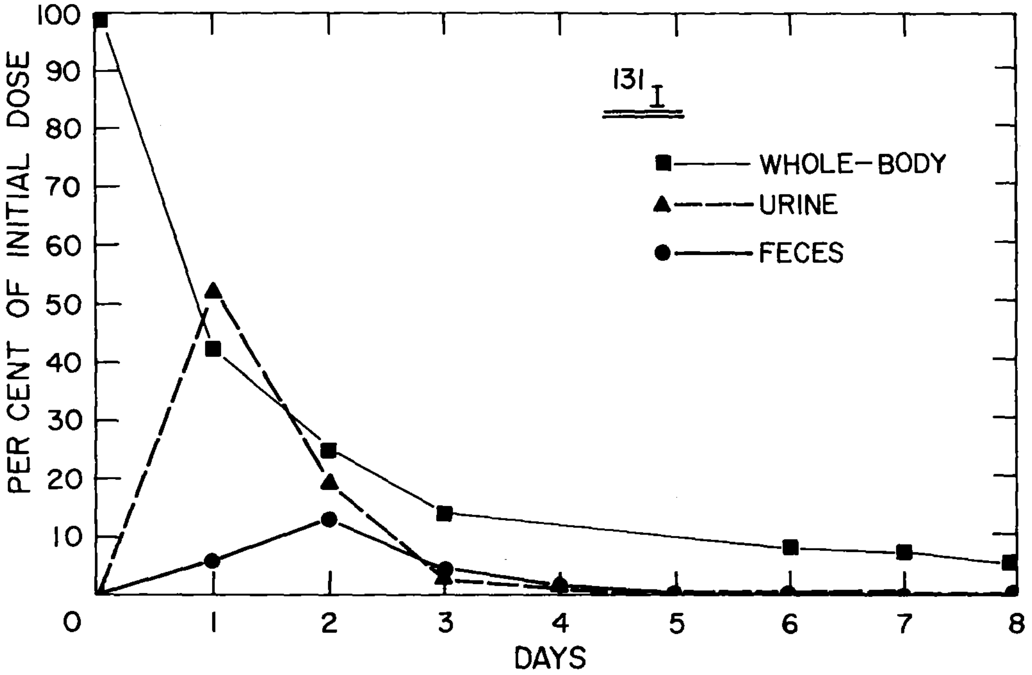

Figure 10. Uptake, retention and excretion in pig of iodine-131 from debris from Plowshare cratering event that was orally administered to the animal.

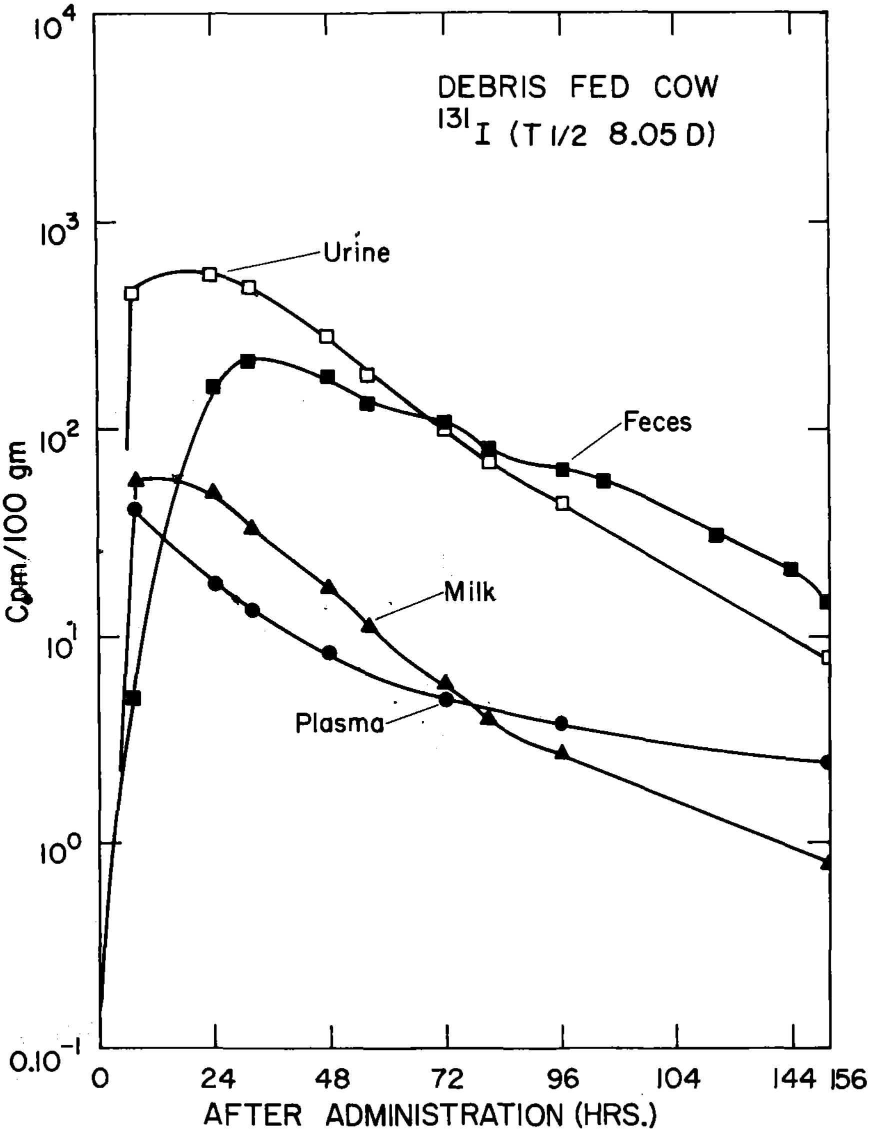

Figure 11. Iodine-131 content of milk, plasma, urine and feces of lactating cow fed nuclear debris from a Plowshare cratering event.

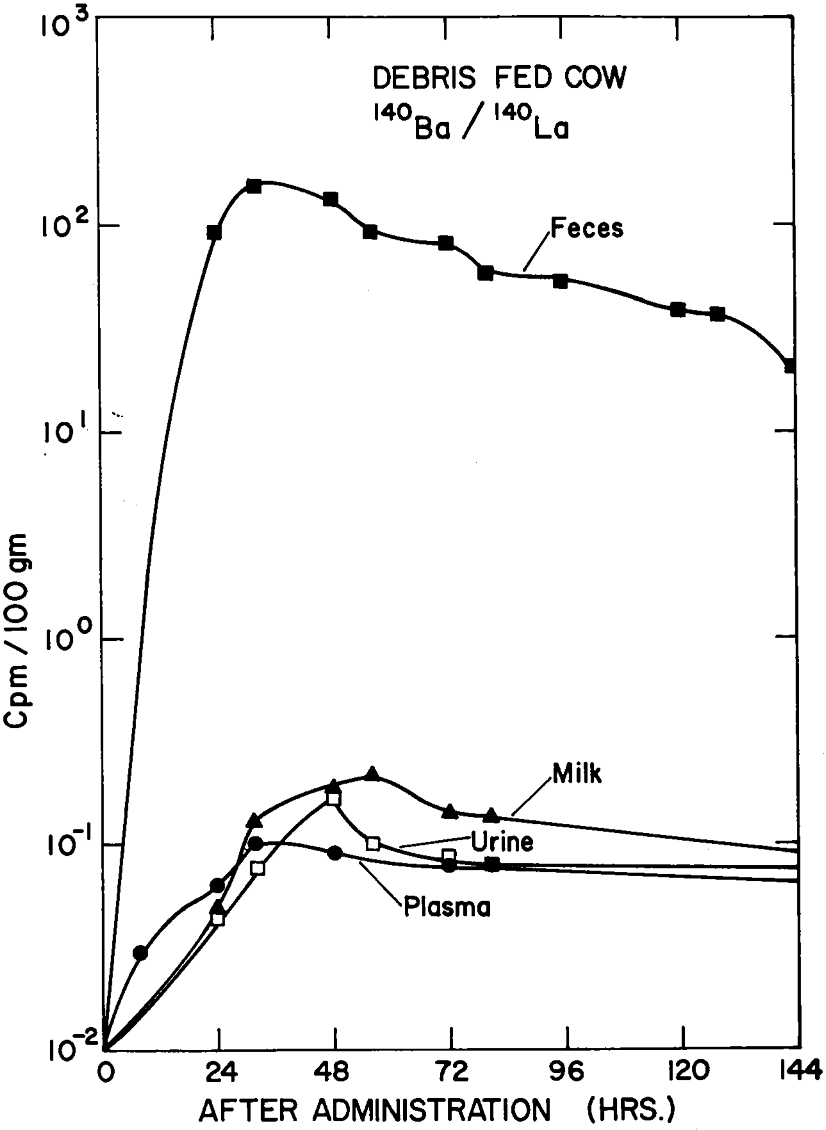

Figure 12. Barium-140/lanthanum-140 content of milk, plasma, urine and feces of lactating cow fed nuclear debris from a Plowshare cratering event.

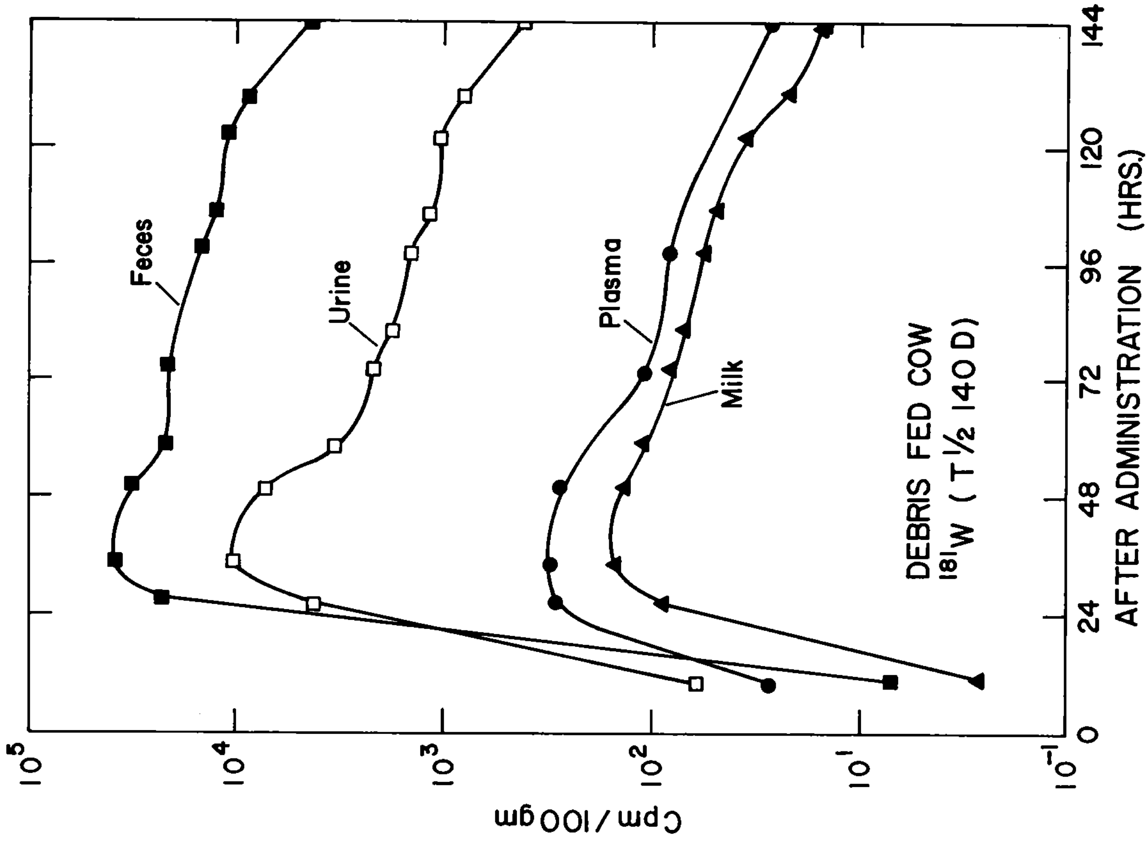

Figure 13. Tungsten-181 content of milk, plasma, urine and feces of lactating cow fed nuclear debris from a Plowshare cratering event.

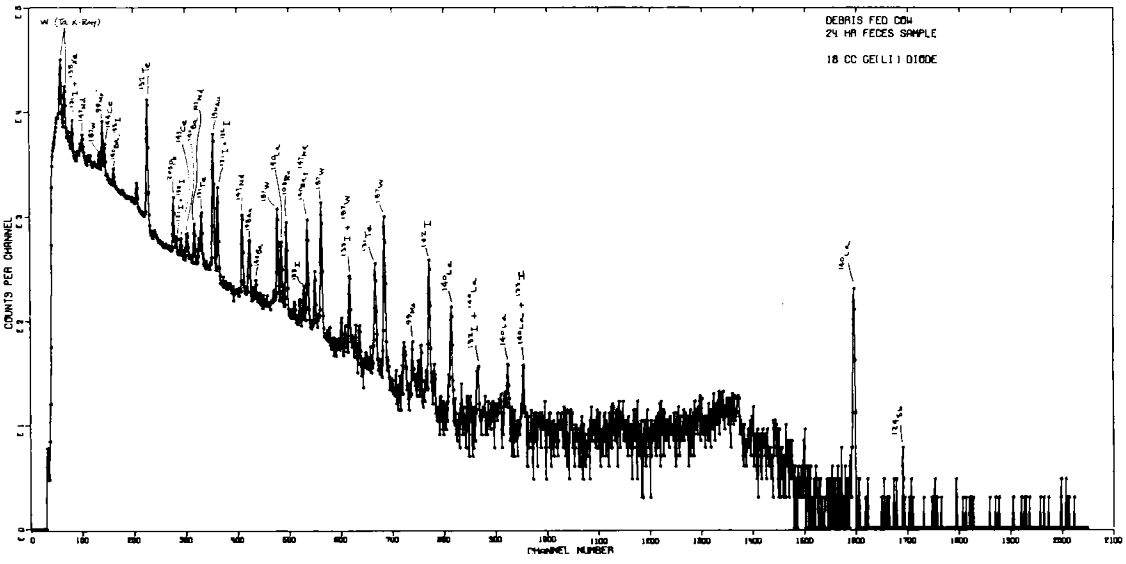

Figure 14. Radionuclide content of feces of animal fed nuclear debris from a Plowshare cratering event.

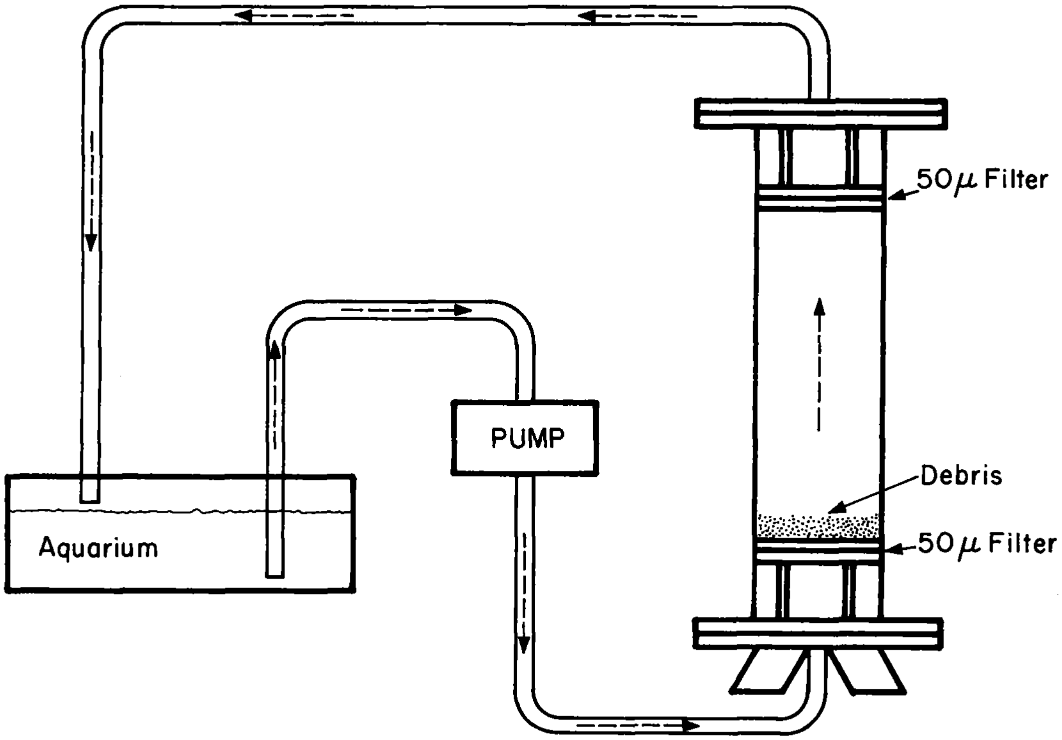

Figure 15. System used in determining biological availability of Plowshare cratering debris to aquatic animals.

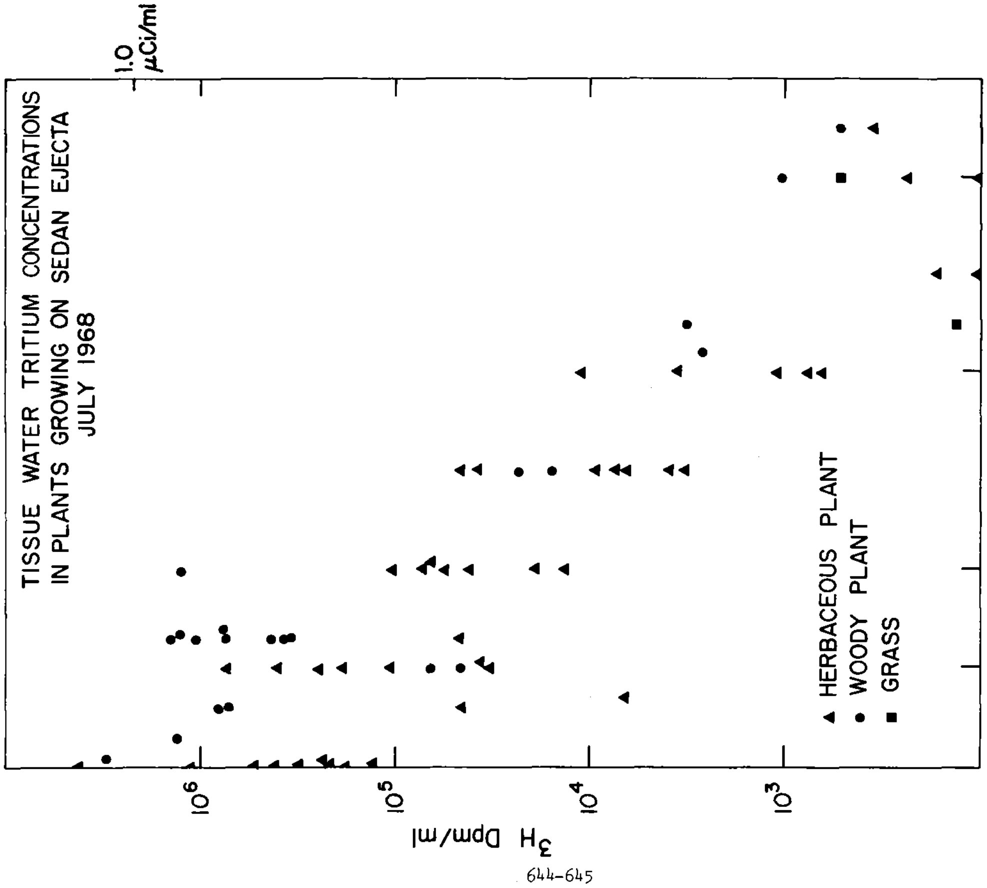

Figure 16. Tissue-water tritium concentrations in plants growing on Sedan ejecta at Sedan Crater.

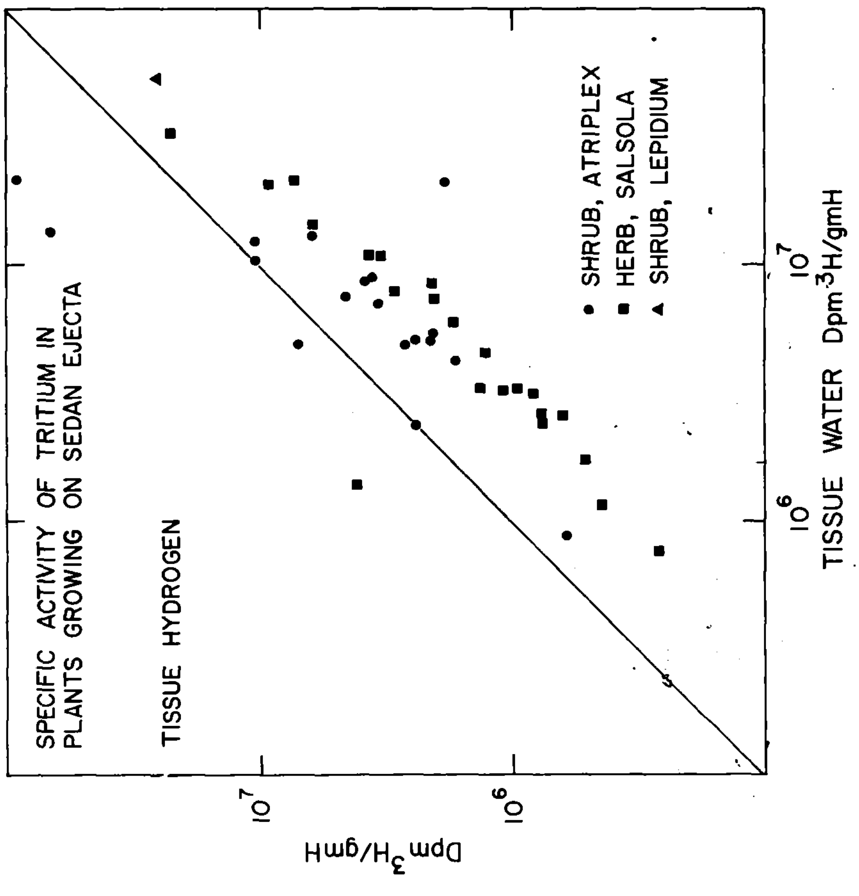

Figure 17. Specific activity of tritium in plants growing on Sedan ejecta.

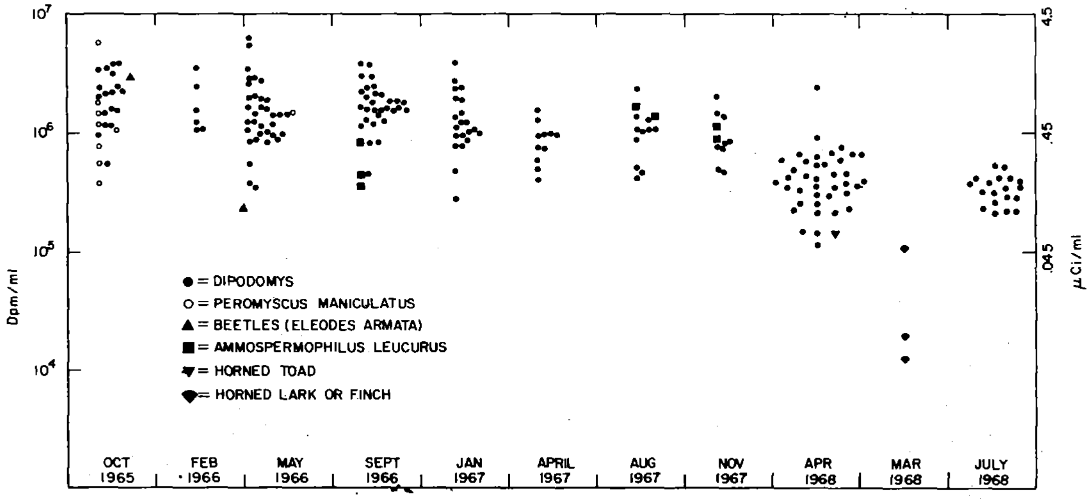

Figure 18. Body-water tritium concentrations in mammals living at Sedan Crater.

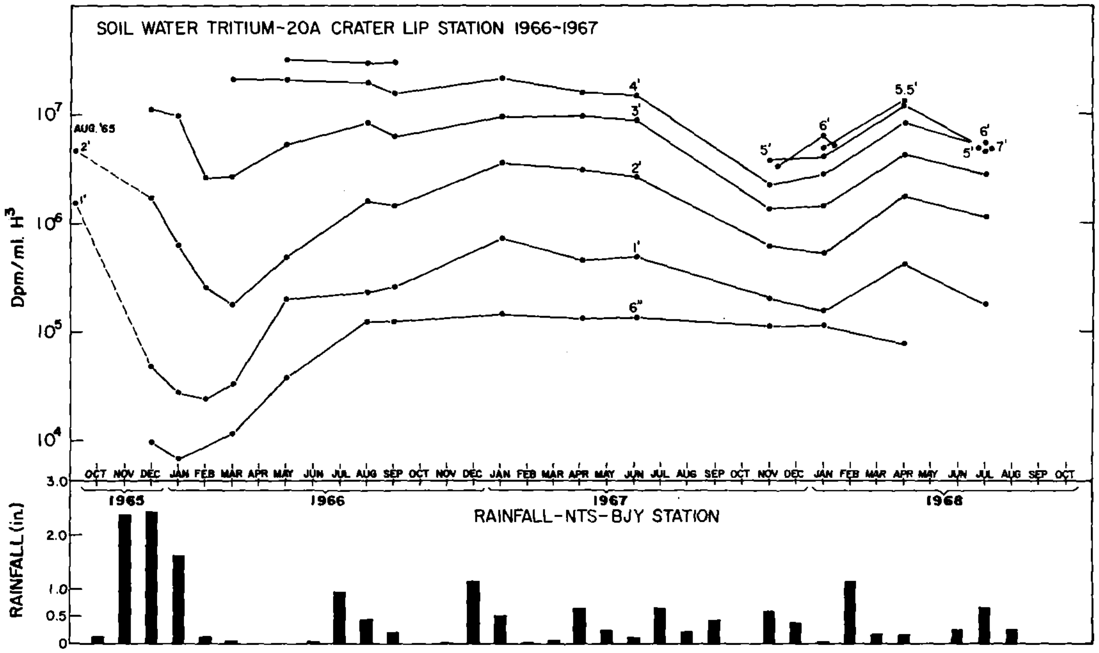

Figure 19. Effects of seasonal rainfall on soil-water tritium profile in Sedan ejecta.

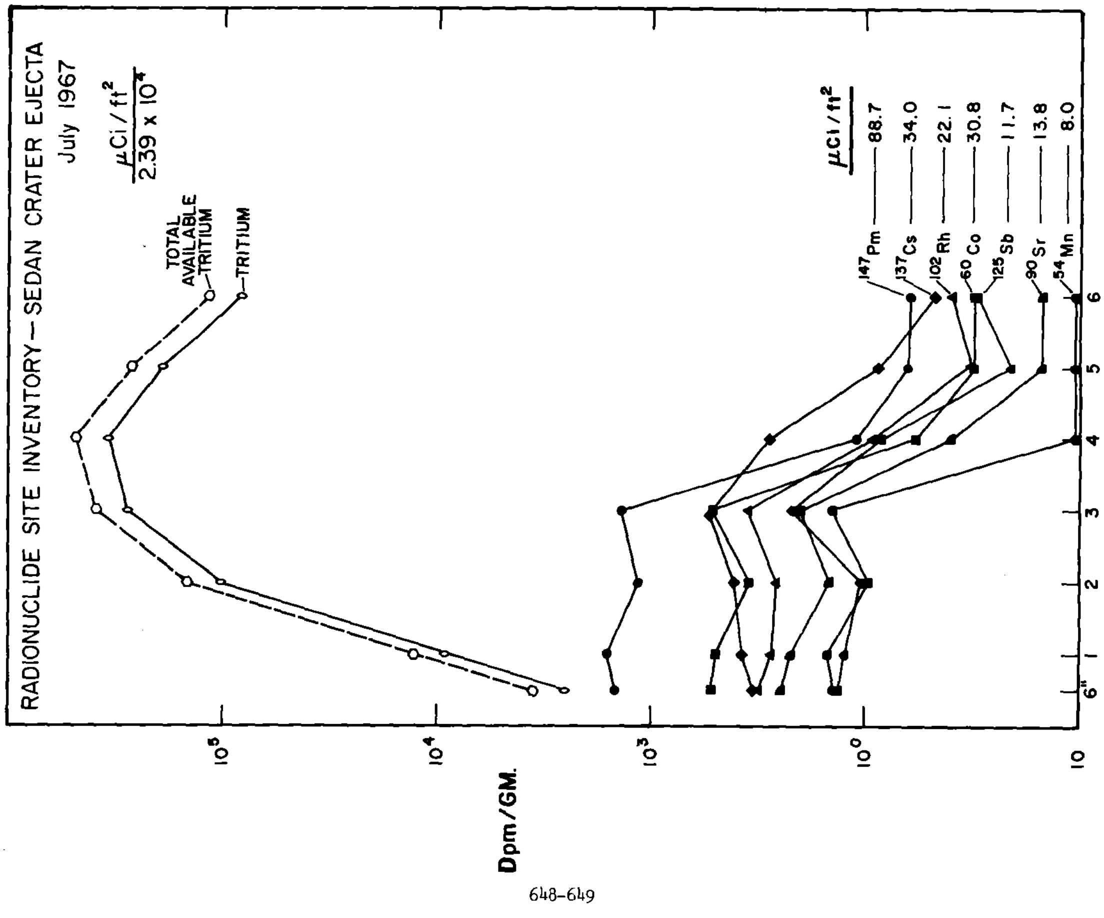

Figure 20. Inventory of tritium and other radionuclides at Sedan Crater.

QUESTIONS FOR BERNARD W. SHORE

1. From Dr. Sternglass:

   To what extent is research planned to follow up on the indication that strontium-90 may be incorporated in genetic material leading to increased fetal and neonatal deaths both in experimental animals and man?

   ANSWER:

   The first thing I would want to say is the processes of data would indicate that strontium-90, when incorporated in genetic material, will result in increased fetal and neonatal deaths both in experimental animals and in man. The other point I would like to make is that the AEC and the National Institutes of Health are supporting much research in the area of low dose effects of radiation and these studies include studies on the effects of strontium-90 on genetic material; we do some in our own laboratory, but the tests have not been developed. But I think in the past the problem has been one of developing an appropriate system. Quite obviously the system has to be one at the genetic and biochemical level because the changes you see are going to be very small and are going to require a lot of what is called basic or fundamental research in this area. It might very well be that the limit on strontium-90 or any environmental pollutant does require research until we know what causes cancer or causes leukemia, what causes unbalanced cell growth, and one of the fundamental processes of regulation and control in humans or animals. So research is being done in the area of relationship between radionuclide and population and in genetic material such as chromosomes and nucleic acids and their possible effect on fetal and neonatal deaths.

2. From Darryl Randerson:

   You mentioned that your gamma-ray spectrometer could resolve radionuclide concentrations as small as 0.02 picocuries. What is the significance (accuracy) of this number? What are the advantages of your spectrometer measurements as compared to activation analysis techniques which have as good or better resolution?

   ANSWER: (Paul Phelps)

   The significance of being able to detect very low levels of radionuclides allows the establishment of uptake by plants and animals subjected to low levels of fallout. For example, 10 pCi of cesium-137 contained in two liters of cow's milk can be ascertained to an accuracy of ± 20%. In addition, this spectrometer may be used for determining activation products produced by neutron activation procedures. In fact, the quality of neutron activation analysis is dependent upon the resolution of the spectrometer.

Activation analysis has no applicability for determining radionuclide contamination, but is very useful in elemental analysis.

RADIOLOGICAL SAFETY RESEARCH FOR NUCLEAR EXCAVATION PROJECTS - INTEROCEANIC CANAL STUDIES

A. W. Klement, Jr.
U.S. Atomic Energy Commission
Las Vegas, Nevada

ABSTRACT

The general radiological problems encountered in nuclear cratering and nuclear excavation projects are discussed. Procedures for assessing radiological problems in such projects are outlined. Included in the discussions are source term, meteorology, fallout prediction and ecological factors. Continuing research requirements as well as pre- and post-excavation studies are important considerations. The procedures followed in the current interoceanic canal feasibility studies provide examples of radiological safety problems, current solutions and needed research.

* *

Many of the papers presented at this symposium have discussed research directed toward development of radiation protection guidance for Plowshare projects or the application of such guidance. There are several areas in which radiological safety problems can be attacked in this regard. These will be discussed here in terms of current approaches and some of the requirements for their improvement. The context in which they are presented here may be broader than some workers in the field would consider. Much of this discussion will reflect experience in the current interoceanic sea level canal feasibility studies conducted under the auspices of the Atlantic-Pacific Interoceanic Canal Study Commission. In these studies, a great deal of research has been conducted and additional needs have become apparent. A brief description of the interoceanic canal studies will be given here, especially of the nuclear safety aspects. For more detailed information on the overall program, reference is made to other publications (1-5).

The objectives of the interoceanic canal studies are to investigate the various aspects of construction of a sea level canal in the

American isthmian region. Primary consideration is given to excavation along routes in the vicinity of the Panama Canal by conventional means (Routes 10 and 14) and along routes in eastern Panama (Route 17) and northwestern Colombia (Route 25) by nuclear means, or a combination of nuclear and conventional means (Figure 1). Under consideration for nuclear excavation is a canal cross section providing a navigation prism 1,000 feet wide and 60 feet deep. Route 8, along the Nicaragua and Costa Rica border, involves a conceptual study only and will not be discussed here. Initial possibilities that were considered for nuclear excavation along Routes 17 and 25 included the elements in Table 1. While studies of the plans for excavation have not been concluded and will undoubtedly be different from these, this table indicates the extent of the program under consideration.

In connection with these studies several comprehensive programs were established and are continuing. The Atomic Energy Commission's role in these studies included nuclear safety programs in (1) airblast, (2) ground shock, (3) radioactivity, and (4) nuclear operations. Of these, the radioactivity studies are by far the most extensive. Other studies conducted by the Army Corps of Engineers, which to some extent provide information of importance to nuclear safety activities, include (1) topography, (2) geology, (3) hydrology, (4) medico-ecology, (5) nuclear excavation design, and (6) conventional engineering. While the discussion here is directed toward radiological problems, these should be kept in context with the overall purpose and other problems of equal or greater significance.

An assessment of a radiological situation in connection with a nuclear excavation project involves a number of factors. First, a description of the kinds, nature and amounts of radioactivity produced in proposed nuclear detonations is required. Also, the time sequence of radionuclide production is important. Together these may be designated the "source term." The nuclear devices contemplated for future excavation projects are relatively low in fission nuclide production. Much of the radioactivity produced will be through neutron activation of surrounding materials. While many of the radionuclides so produced are short-lived, they must be considered from the standpoint of total amounts produced. Therefore, the ability to estimate production of these nuclides becomes important. Through tests in the Plowshare program reliable estimates can be made of neutron-activated material associated with the device, as well as the fission products. This constitutes one area requiring study along with device design experiments.

Radionuclides produced through neutron activation of environmental material surrounding the device are, of course, dependent on the elemental constituents of the material which varies with geographical locations. Estimates of production of these radionuclides must be based on assumed constitution of the media in which devices will be emplaced. Where samples of such media can be obtained and chemical analyses made, the assumptions involved are improved. For feasibility studies of large-scale nuclear excavation projects, such as the proposed sea level canal, it is not practical to examine material at such emplacement site. However, data obtained from a variety of formations and geographical locations provide a basis for estimating a range of values for activation products. In general, it would seem that these estimates would be adequate for planning purposes. Additional experience through testing in different media may improve our ability in this regard.

The next area of concern is the distribution of radioactivity in the detonation process. Because of its immediate importance, atmospheric transport and deposition is considered first. The elements required for estimation of atmospheric transport and deposition include estimates of the radioactivity released to the atmosphere. This varies over a wide range for a given nuclear yield and depth of burial; again, it is dependent on the detonation environment. Also again, the better the environment is known, the better assumptions can be made in this regard, and our ability to predict these factors will improve through testing in different media. Based on some actual geological data estimates of these factors were made in the canal studies. A similar situation exists with regard to the dimensions of nuclear clouds, another important element in predicting fallout.

Through theoretical considerations and a great deal of experience in atmospheric weapons tests, close-in or local fallout prediction models have been developed which have proven reliable within the uncertainties of the elements mentioned above. These, of course, require knowledge of meteorological conditions. Here, it is important to have reliable data, more than climatological. For preliminary or feasibility studies, it is necessary to ascertain the frequency of favorable conditions, i.e. conditions under which fallout is confined to acceptable radiation levels within a designated sector or zone. Where such information is poorly known (and orographic situations require assessment), field programs are required to obtain it as is the case in the canal studies. With these data and assumptions, estimates can be made of locally deposited radioactivity. However, areas of weakness in our ability to assess this factor are (1) washout and rainout effects, (2) transport and deposition of tritiated water, and (3) transport and deposition beyond the local fallout zone. These, especially the first two, are not at all well-known and constitute items needing further research.

The remainder of the technical problems with assessing radiological situations deal with biological transport and its consequent effects on man. The external gamma radiation situation can be assessed from the treatment of deposition mentioned above. Situations so assessed which indicate an unacceptable situation obviously preclude the need for assessment of possible internal human radiation exposure. However, the latter contributes to total exposure and in certain cases can be critical. It is by far the most difficult assessment to make because of its complexity and its dependence on specific environmental information. The process involves tracing radionuclides through food webs to man. Here, it is necessary to consider also the radioactivity which was not released to the atmosphere. For example, ground water contamination needs consideration. Information required includes data on human populations and habits, particularly dietary data. The nature of the population and its habits will determine the ecological data needed. These, of course, vary widely with geographical regions as does the extent of available knowledge concerning them. As in the canal study situation, field studies to some degree at least are required.

Mathematical models, ranging from very simple to highly complex, have been developed to estimate internal radiation exposures to human populations. In general, the very simple models are highly empirical and leave much to be desired in assessing complex situations. On the other hand, the highly sophisticated models require data which are not available and are highly theoretical, perhaps only mathematically. Compromises have been suggested which appear to be practical, even though some assumptions must be made. In general, reasonable and practical field studies supplemented by existing information can provide the basic animal and plant population data required. A great deal is known with regard to many food webs and transport of a number of radionuclides through them. For some food webs and some radionuclides, it is necessary to make assumptions, and in a number of cases with few current bases. It is in these areas where continued and additional research is required. The behavior of some elements in man should be among these research goals.

The effects of radiocontamination of plants and animals other than man, as it may indirectly affect man, should be considered. In some cases, because of other activities (rapid urbanization or development) radiation effects could easily be dismissed. In any case, some assessment is possible at present.

The last element to be discussed here is radiation protection guidance. To some extent all of the above should be considered in discussions of radiation protection guidance. The application of our knowledge of radiation effects, and the lack of it, to the establishment of guides are obvious and have been discussed by others here. Considerable research is being conducted in this area, and as methods and techniques improve, the bases for radiation guides will become more sophisticated. As mentioned above, some advances can be made through research into the behavior of certain radionuclides in man. The major problems in the area of radiation protection guidance seems to be in the application and interpretation of guidance. Arguments of these problems often go far beyond our technical knowledge. The balance of risk and benefit concept is a difficult one to apply. The scales used for the balancing are seldom adjusted properly. This is an area where the researcher as well as the applied scientist and engineer can contribute to solutions of problems. If the problem is approached and reported in a scientific manner, at least the balancing process can be made easier in many respects.

The current interoceanic sea level canal feasibility study offers a good example of problems in radiological safety, along with other safety problems. The proposed project is the largest and most complex of any to date which could involve nuclear excavation. Also, it has involved the most detailed study of radiological safety of any proposed project to date. The approach being used in the studies involving nuclear excavation will be described briefly below.

The studies were begun assuming nuclear excavation designs for Routes 17 and 25 developed in the 1964 study which are summarized in Table 1. The final plans, yet to be arrived at, will depend on geological investigations, current cratering technology and safety considerations. Based on these preliminary designs and future nuclear devices contemplated for the projects, estimates were made of the radionuclides that would be produced in each detonation (6, 7). As mentioned above, the chemical composition of media of detonation points were assumed initially. Based on nuclear cratering experience to date and assumed geology, the percent of radioactivity entering the atmosphere and cloud heights were estimated for each detonation (4). These provided preliminary source term information.

Also, the radionuclides produced were analyzed as to their possible importance with regard to internal radiation dose to man. This involves a process of elimination from a list of several hundred radionuclides. A number of these can be eliminated on the basis of their very short half-lives or the very small quantities produced. The remainder are analyzed (8-10) from the standpoint of their contribution to potential total internal radiation exposure, either to critical organs or whole body exposure. For this purpose, data for and methods of estimating exposure recommended by the International Commission on Radiological Protection (ICRP) were employed. In addition, analyses were made employing the specific activity concept in a very conservative manner (7, 9, 11). For example, one can arrive at "Maximum Permissible Specific Activities" (MPSA's) based on ICRP values of Maximum Permissible Concentrations (MPC's) and stable element concentrations in "Standard Man." From these a list can be made of the relative importance of each radionuclide, then assuming the MPSA's to be reached, those contributing to about 99% of the internal dose can be determined. The remainder would be of little significance. Other similarly conservative estimates can be made, thus confirming the adequacy of this approach. The purpose of this analysis is not to ignore some radionuclides but to determine which require more intense study and especially to determine which stable element analyses should be made in field samples.

Two weather stations were established on each route being considered for nuclear excavation. From these stations meteorological data were obtained for fallout prediction purposes (4). Operations were for about 18 months on Route 17 and will be for about 24 months at one station on Route 25 (June 1969). Using wind data obtained over about a year, preliminary estimates of fallout indicated an area which may require evacuation of the indigenous population. Subsequently, an analysis was made to determine the days on which specific detonations could be conducted and the fallout confined to this exclusion zone. A similar process was carried out to determine days on which there would be no long range airblast damage. This provided an overall calendar of acceptable days for all proposed detonations. With these a schedule for each detonation was made for planning purposes. Using this schedule, all available meteorological data available, and a rapid computer model developed for this purpose, specific fallout predictions were made for Route 17 excavation. The latter are currently in process for Route 25.

These predictions are in the form of external gamma lifetime isodose contours for each detonation and a total for all detonations. From basic source term data, these can be converted to quantities of each radionuclide deposited. These provide a preliminary basis on which to assess the radiological implications involved in nuclear excavation. The total lifetime external gamma 0.1 R isodose contour for Route 17 was well within the initially selected exclusion zone. However, because of the uncertainties involved in the estimates and the possibility of unusual changes in wind patterns, it was not felt that the exclusion area should be reduced in area.

Concurrent with the meteorological field studies were other studies. Among these were ecological investigations (8). These consisted of literature, field and laboratory studies in human, terrestrial, freshwater, marine, and agricultural ecology, as well as hydrologic modeling studies. These provided a reasonably detailed description of the areas in the various fields although, except for seasonal variations, few studies of dynamics were made. Human populations were described with regard to location and dietary customs, as well as other demographic variables such as population-area trends of the various groups. About five distinct population groups are involved.

Food webs leading to man were identified and elemental chemical analyses of environmental samples provide information on the biological availability and concentration of stable elements in the various systems. With these data, ecological transport models can be realistically modified to represent more nearly the actual situation, and assumptions of radionuclide transfer coefficients are facilitated. As mentioned earlier the latter are currently poorly known for many situations, and this is so particularly for the geographical areas of interest to the canal studies. However, with the field and laboratory data along with available data in the literature, it is felt that reasonable assumptions can be made.

The overall dose estimation model provides for total radiation dose estimates, internal and external. Estimates are made for each distinct population group and for elements within each group, e.g. infants. This process of dose estimation has not yet been completed.

As mentioned throughout this discussion, a number of initial or preliminary assumptions were used in the assessment. Nuclear excavation plans may change because of various factors such as actual geological data obtained, the results of chemical analyses becoming available (12), and additional experience in test programs. Also, changes may be made in nuclear device design and thus in the radioactivity produced. As these changes are made or occur, the radiological situation must be reassessed. In fact, while it does not appear probable from information available to date, it is possible that nuclear plans may require changes to provide more favorable radiological situations.

One of the important objectives of a feasibility study is to determine where problems may exist and suggest operational solutions to them. For this reason the studies mentioned here include analyses of operational methods and techniques as integral parts of the studies. It is here that provisions are made for uncertainties in estimates. In nuclear operations plans are included facilities for detailed timely forecasts of radiological situations for each detonation and means of limiting detonations to times when situations will be most favorable from the standpoint of safety. Also, included are provisions for surveillance of situations following detonations and means for initiating countermeasures on a timely basis.

Along with the studies described here, an analysis of existing radiological protection guidance was made (10), since comparison of estimates with some guidance is necessary to an evaluation. The establishment of protection criteria for nuclear excavation of a canal is clearly beyond the scope of the canal feasibility studies, and no attempt will be made to do this. However, it is felt that the studies will be useful in this regard and some possibilities will be suggested. The approach in the canal studies has been to present the best estimates possible in a scientific manner so that a balance of the benefits and risks can be made as objectively as possible. The results will be presented so that comparison with any criteria will be possible. Perhaps the judgement involved in this balance should be among the bases of radiation protection guidance established for this and other specific applications of nuclear energy. Perhaps research, in its broader aspects, along such non-technical lines is as important as approaches to the biological effects of radiation.

REFERENCES

1. Atlantic-Pacific Interoceanic Canal Study Commission. 1968. Fourth annual report. Washington. iii, 67 pp.

2. Hughes, B. C. 1968. Nuclear excavation design of a transisthmian sea-level canal. Trans. Am. Nuclear Soc. 9(2). (Also, U.S. Army Engineer Nuclear Cratering Group, Livermore, California, tech. memo No. 6).

3. Battelle Memorial Institute. 1967. Bioenvironmental and radiological-safety feasibility studies, Atlantic-Pacific Interoceanic Canal. Colombus Labs., U.S. AEC report BMI-171-003. 99 pp.

4. Ferber, G. J. and R. J. List. 1969. Prediction of external gamma dose from nuclear excavation. BioScience 19(3). (in press)

5. Martin, W. E. 1969. Bioenvironmental studies of the radiological-safety feasibility of nuclear excavation. BioScience 19(2): 135-137.

6. Vogt, J. R. 1969. Radionuclide production for the nuclear excavation of an isthmian canal. BioScience 19(2): 138-139.

7. James, R. A. and E. H. Fleming, Jr. 1966. Relative significance index of radionuclides for canal studies. University of California, Livermore, U.S. AEC report UCRL-50050-1. 10 pp.

8. Various. 1969. (Along with references 4-6, 20 papers dealing with radiological safety in the canal studies program will appear in BioScience during 1969. Also a series of reports on the various ecological and radiological safety studies have been issued as U.S. AEC reports BMI-171-001 through -016, including references 3, 10, and 11 listed here).

9. Kaye, S. V. and D. J. Nelson. 1968. Analysis of specific activity concept as related to environmental concentration of radionuclides. Nuclear Safety 9(1): 53-58.

10. Cowser, K. E., S. V. Kaye, P. H. Rohwer, W. S. Snyder and E. G. Struxness. 1967. Dose-estimation studies related to proposed construction of an Atlantic-Pacific interoceanic canal with nuclear explosives: Phase I. Oak Ridge National Laboratory, U.S. AEC report ORNL-4101. x, 210 pp.

11. Lowman, F. G. 1967. Phase I - final report, estuarine and marine ecology. Puerto Rico Nuclear Center, Battelle Columbus Labs., U.S. AEC report BMI-171-007. 85 pp.

12. Hill, J. H. 1968. Chemical analysis of samples from interoceanic canal Route 17. University of California, Livermore, U.S. AEC report UCRL-50555. 66 pp.

TABLE I

PRELIMINARY EXCAVATION DESIGN DATA (ISTHMIAN CANAL STUDIES-1964)

	Route 17 (48.5 Mi.)	Route 25 (39.3 Mi.)*
No. Detonations	22	19
Devices per Row	4-38	4-45
Device Yields	200 KT - 10 MT	Same
Depth of Burial	675 - 2100 Ft.	Same
Total Yield per Row	8.4 - 30 MT	9 - 30 MT
Total No. of Devices	267	223
Total Yield per Route	292 MT	245 MT

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*Total length 100 mi.

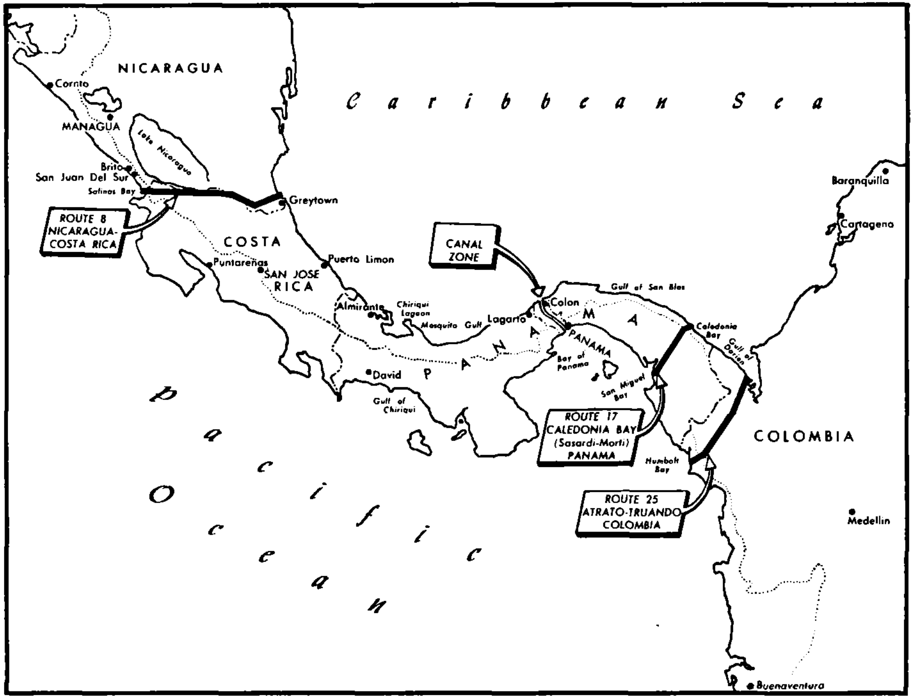

Figure 1. Proposed Sea Level Canal Routes

QUESTIONS FOR ALFRED W. KLEMENT

1. From R. M. Stewart:

   In the Route 17 canal in Panama, what portion of the excavation might be nuclear? What maximum total yield is contemplated?

   ANSWER:

   On Route 17 in the preliminary studies, it was intended that this route be excavated completely by nuclear means. We now have actual geological information on this route and this indicates that there are some problems and we are considering various methods of excavating some 20 miles of that route by a different system of nuclear excavation, a combination of nuclear and conventional, or a completely conventional means. This decision has yet to be made as there are still studies being made on it.

   The maximum total yield contemplated, and again I have to go back to the preliminary design, for any one row charge the highest was 30 megatons. This is still being considered. We would like to reduce this to the lowest we can and still do the job and there is a possibility that this would be done. But at this stage we're some ways from what actual design we have to have to excavate the canal.

2. From George Collins:

   Would you care to comment on possible adverse ecological effects resulting from a sea level canal other than the possible radiological effects? (For example - intermingling of different species of marine flora and fauna from the two oceans.)

   ANSWER:

   This, of course, is an area in which I am not competent. I can only say that a look at this problem is being made under the auspices of the Canal Study Commission by those, hopefully, who are competent. It is not an integral part of the Nuclear Safety Studies of course and it's beyond the general area you would expect our office here to undertake.

3. From E. A. Martell:

   How will physical properties of radioactive cloud debris in the wet isthmus environment compare with those for Nevada cratering tests?

   How well can debris cloud heights be predicted for large yield cratering shots in the wet isthmian environment?

ANSWER:

First of all we have no experience with large scale cratering events anywhere. This is an area we certainly need information on and to continue in a large scale project using large yields, it's essential that the experimental Plowshare program continue in order to obtain information which can be used. At the present time, we are forced to scale from the smaller shots that we have had in Nevada and materials are considerably different. Our largest test, Sedan, in alluvium was very interesting. Along Route 17, I think there is no alluvium.

With regard to the properties of the radioactive cloud, I think this is the same thing. We are still scaling from what experience we have. We certainly need, as I mentioned, experience in various environments in order to get a better handle on this.

4. From Danny T. Carrara:

Over what period of time would the 30 miles of nuclear excavation take place in Model No. 25 if this model is adopted?

ANSWER:

This would depend on the final design. Whatever system is arrived at. It would seem to me, based on our preliminary estimates, that this could be conducted perhaps over a period of 18 months, perhaps two years. Certainly, the data we have indicate that nuclear safety would not prevent us from doing this, but there are other operational problems that may. For example, with Route 25 we're talking about a total construction time for the entire canal on the order of 15 years and the nuclear excavation part of this is relatively small. The same is true of Route 17, except it is a much shorter route and will take a much shorter time.

PLANNING REQUIRED IN THE DEVELOPMENT OF RADIATION PROTECTION GUIDANCE FOR UNDERGROUND ENGINEERING APPLICATIONS

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ABSTRACT

The potential variety of engineering applications from the peaceful uses of underground nuclear explosives indicates an increased need for applicable radiation protection guidance to protect the public health of potentially exposed populations.

To insure the orderly development of such uses, additional operational data as well as bioeffects data will be required to develop appropriate criteria and guidance to inform health officials and the public of the significance of possible exposures. The required planning includes an evaluation of the potential benefits and risks as well as the size and age of population, multiplicity of sources, likely and unlikely future uses, and the total environmental impact.

INTRODUCTION

This paper is addressed to planning in the development of radiation protection guidance for fission products and neutron induced activities incorporated into consumer products resulting from fully contained Plowshare projects. The subject of guidance relating to excavation projects and of applicable guidance in the protection of public health in the immediate post-shot period are both being covered elsewhere in this symposium.

Safety of consumer products is of direct interest to the Department of Health, Education, and Welfare; particularly to the new Consumer Protection and Environmental Health Service of which the Environmental Control Administration is a component.

If the world in which we live had no financial limitations and we were able to work in a totally orderly way, I could present a logical sequence of questions to which we could address ourselves; and as we answered each question, we could then proceed to the next perhaps as follows:

1. What are the actual radionuclides and actual concentrations that will be in each of the consumer products obtained from Plowshare?

2. What are the amounts of consumer products that will be used by the public?

3. What would be the resultant whole body and other organ doses obtained by different populations?

4. Then having satisfied ourselves of the actual quantitative exposures, we could then tackle and answer the question, "What are the long-term effects of this low-level exposure?" Assuming that we could quantitate this risk to everyone's satisfaction, we could then proceed to obtaining a consensus on the levels of risk which would be acceptable to all concerned.

Unfortunately, as we all know, definitive conclusive, absolute answers to these questions cannot be answered to everyone's satisfaction.

But in order to facilitate the constructive use of Plowshare applications for the betterment of society, we must demonstrate what these potential risks of radiation exposure are so they can then be weighed against the anticipated benefits. And this belongs in the public forum.

Congressman Craig Hosmer of the Joint Committee on Atomic Energy emphasized the importance and need to set clear, firm guidance in this area, and he reiterated most strongly the need to help protect the public health by insuring safe consumer products.

Now then, who sets the standards? By law, the Federal Radiation Council has specific responsibilities in providing a first level of guidance to federal agencies. The AEC has been assigned the responsibility of conducting the Plowshare program for the purpose of investigating and developing peaceful uses for nuclear explosives. While the AEC controls the execution of a Plowshare project, the acceptability of any resulting products involves the mutual responsibility of both the Public Health Service and the involved state health departments as well as the general public and the scientific community. In short, the community represented here today has a mutual responsibility and partnership in assessing the health significance of Plowshare projects. Obtaining the required evidence of theoretical calculations and empirically observed data is of greater importance than the identity of the particular organization that may have the last word in setting the allowable exposure level.

DISCUSSION

In August 1959 the President assigned the primary responsibility for the collection, collation, analysis, and interpretation of data on environmental radiation to the Department of Health, Education, and Welfare. The intent was to separate the responsibility of evaluating the radioactive health hazards from the responsibility of encouraging the use and development of radiation. As part of the discharge of this responsibility, the Bureau of Radiological Health has systematically gathered the data on levels of observed contamination of radioactivity in the environment from our surveillance networks, other federal agencies, state health departments, the AEC-sponsored national laboratories and others. They have all been published each month in Radiological Health Data and Reports, with interpretive analysis when possible and without interpretation if time did not permit. In this manner the results have been available for interpretation by the scientific community as well as the general public. The importance of publishing the data in the public forum to permit independent evaluations cannot be overly stressed.

Perhaps the most important element of any planning is the need to educate the public to the facts. I think we can safely anticipate concern and fear (whether real or imagined) from certain sectors of the public and I think the most vital ingredient in our planning is imagination--imagination to anticipate the questions which will be raised. We must be able to present the data and the interpretation of the data and have it available for others to interpret.

The PHS is pleased to sponsor this symposium since it provides an ideal mechanism to bring together all of the diverse interests involved in the public health aspects of Plowshare, including the Federal Radiation Council, the AEC, other federal agencies, state health department officials, representatives of industry, AEC laboratories and many others. And in bringing us together, it provides a mechanism to present the different points of view depending upon one's primary interest in Plowshare.

As a representative of the PHS, I would like to comment on the philosophy of "unnecessary radiation exposure." If we consider a dose-effect relationship from ionizing radiation, we can observe effects in a population at very large doses. Increases in the dose can produce an increase in the incidence of an observed effect. The order of magnitude of such doses required to produce such effects involves levels of exposure of 50 rem or several hundred rem depending on the particular study being referenced. The levels that we are concerned with here are of the order of a few times natural background which is 0.1 rem per year. The question arises as to how one can extrapolate the observed data back by a factor of 500 or 1,000 which is the region of public health interest. What is the shape of the curve? While the evidence of the Russels at Oak Ridge suggests the presence of a threshold in mice, we can ill afford to make such an assumption. So we extrapolate linearly without using a threshold.

If one assumes that the incidence of an observed effect is attributable to natural background radiation, values of 10^{-5} for the probability of observing an effect in a population could be noted. Two extreme positions that have been taken from this are as follows: Multiplying the probability of 10^{-5} times the U. S. population of 2×10^8 would produce 2,000 effects. Hence producing a man-made increment in dose equal to natural background would result in 2,000 effects in the U. S. population. This is a patently absurd mathematical extrapolation.

The second extreme position that has been espoused is to say that the probability of an effect in an individual of 10^{-5} is so small as to constitute a negligible risk to an individual and can be forgotten. This extreme position is equally absurd.

The correct conclusion to be drawn here is to avoid unnecessary radiation exposure, and I think we all recognize the shared responsibility or partnership in endeavoring to reduce all unnecessary radiation exposure in our planning.

Recently one witness at the Joint Committee on Atomic Energy hearings on effects of radon daughter products in uranium miners suggested that we should await the epidemiological evidence of observed effects in the miner population before establishing a lower level of permissible exposure. This approach is untenable to me.

Congressman Hosmer stated and stressed the importance of developing standards for radioactivity in consumer products to insure proper protection of the public.

The radiation protection guidance must establish not only annual doses but must also address itself to the rate of accumulation of dose. For example, while the cumulative thyroidal doses to children from iodine-131 in fresh milk during the decade beginning in 1957 are observed to be far less than the cumulative radiation protection guides, the rate of exposure in 1957 of 1 rem/year exposed those born in those years at a rate of 10 times natural background.

FACTORS IN THE DEVELOPMENT OF RADIATION PROTECTION GUIDANCE

Perhaps one of the most succinct statements regarding the development of effective standards for the protection of man's health was made by the Surgeon General of the Public Health Service, Dr. William H. Stewart, at the hearings held by the Senate Commerce Committee in August 1967. He stated the following:

"1. The standards should be truly relevant to man's health. We must assure that such a standard is addressed to the prevention or control of a health hazard in man's environment.

"2. The standard must be realistic and attainable. A health protection standard must be attainable within the state of the art and at a financial cost which is not truly prohibitive. Otherwise, the standard would become in fact a flat prohibition rather than a charter for prudent continuation of a desirable activity under conditions not injurious to human heal health.

"3. Adherence to the standard should be measurable with reasonable precision and reliability. Those responsible for enforcing the standard must be able to ascertain when a violation has taken place; and the great majority of manufacturers who will wish in good conscience to comply with the standard must be able to ascertain that they are indeed doing so.

"4. The standard should be aggressive in terms of protecting the public health. Uncertainties as to the degree of control necessary should, in general, be resolved in that direction which will afford the greatest protection to the public."

Other necessary factors include:

1. Better understanding of the links in the chain of radioactive exposure to man of the general environment, man's immediate environment, intake, body burden, dose rate, dose and effects.
2. Monitoring and surveillance networks to demonstrate the presence or absence of radioactivity by observed measurements in the above-mentioned chain for both alerting and assessment purposes.
3. Better identification of the population-at-risk from a particular application considering age, sex, dietary habits, physiological habits and other parameters.
4. Designing and testing mathematical models based on the data being obtained.
5. Anticipating the diverse multiplicity of sources to be encountered.
6. Establishing guidance that is clear and readily interpretable by industry, health officials and the public.

The challenge exists to use Plowshare applications to help solve other public health problems. Ionizing radiation is being used to meet and help solve the problems encountered in other areas of public health such as waste disposal, water pollution and air pollution, and we have a challenge to use Plowshare applications equally as well.

And lastly, I hope that we would plan on using the planning.

QUESTIONS FOR ROBERT NEILL

1. From James Leonard:

   In reference to the benefit-risk concept as applied to problems of radionuclides in the environment, do you see any role for public opinion surveys in determining acceptable activity levels? For example, should the public be asked such questions as these: Would you favor use of nuclear explosives to reduce the cost of natural gas delivered to your home by "x" cents per million BTU's if such use increased the probability of some form of radiation-initiated health effect (say an increase in still births by "y" incidences per 100,000 population)?

   ANSWER:

   No, I dont' think questions such as these should be relegated to a public opinion poll, nor that one should decide these things by personal opinion. I think, however, that the mechanism, for example this Symposium which we are holding here today, in bringing together under one roof the various interests, certainly the legislative interests in the presence of Congressman Hosmer of the Joint Committee indicating his concern and interest in the area of public health aspects of Plowshare applications, as positive evidence of this fact.

2. From James Leonard:

   Would you favor use of nuclear explosives to reduce the cost of natural gas delivered to your home by "x" cents per million BTU's if such use increased the probability of some form of radiation-initiated health effect?

   ANSWER:

   This is rephrasing this general question that I said that it would be so nice to have a final, conclusive, definitive, absolute answer to solve to everyone's satisfaction as to what constitutes the long-term effects and what is an acceptable risk. I think, though, that we all have a shared responsibility in assessing this and I, for one, would not be in a position today to try to describe the specific amount in which I would be involved here.

SESSION VI - SOME IMPLICATIONS OF LARGE SCALE USE OF PLOWSHARE TECHNOLOGY

Chairman: Mr. William M. Trenholme
Arizona Atomic Energy Commission
Phoenix

INDUSTRY POTENTIAL OF LARGE SCALE USES FOR PEACEFUL NUCLEAR EXPLOSIVES

Paul L. Russell*
Bureau of Mines
Denver, Colorado

ABSTRACT

The industrial potential for peaceful uses of nuclear explosions is entering a critical stage of development. Should Project Gasbuggy, an experiment to determine to what extent an underground nuclear explosion can stimulate the production of natural gas from low-permeability formations, prove a technical or economic success, a great step forward will have been made. Should other experiments now being considered in natural gas, oil shale, copper, coal, water resources, underground storage, and others, also demonstrate technical or economic advantage, it is conceivable to expect peaceful nuclear explosions to grow from our current rate of one or two experimental shots per year to hundreds of production explosions per year. This growth rate could be severely restricted or reduced to zero if public safety and environmental control cannot be exercised.

SUMMARY

The use of nuclear explosives has been proposed for a wide range of peaceful applications. Such use will be made only if nuclear explosives show economic advantages over conventional explosives. To date we have no demonstrated economic commercial application. Until the experimental research program shows that economic use is feasible and practical, nuclear explosives will be used for research, and the total number of experiments per year will be small.

This paper reviews the principal proposed peaceful applications for nuclear explosives and discusses each proposed use briefly. An estimate of future requirements for nuclear explosives is made.

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INTRODUCTION

As early as 1945 the possibility of using nuclear explosives for peaceful purposes was a subject for speculation. By June, 1957, the Plowshare Program was formally established by the Atomic Energy Commission (AEC) for the purpose of developing and demonstrating such peaceful applications. Since the first underground experiment in the fall of 1957, the AEC has conducted well over 200 underground nuclear explosives as well as a small number of surface cratering tests.

Although the majority of these nuclear tests were defense oriented, they, and a few Plowshare shots, have all contributed data useful in the development of peaceful applications. Tests have been conducted in eight rock types--tuff, salt, basalt, dolomite, granite, rhyolite, alluvium, and sandstone--providing a wide variety of data on many aspects of rock fracture and breakage, ground shock, and radioactivity. This information was used in planning the apparently successful Gasbuggy experiment in sandstone, and is the basis for planning other Plowshare projects.

This paper will list and briefly discuss most of the proposed peaceful applications for nuclear explosives. It will also consider the apparent numerical requirements of future use and consider timing of such needs. Technology of nuclear explosive use will be covered very briefly, since this alone is a major subject.

NUCLEAR EXPLOSIVES

Nuclear explosives are unique. They release vastly larger quantities of energy per volume and at a rate a thousand times more rapid than the fastest chemical explosive. Nuclear devices are compact, being packaged in a case 7 to 14 feet long and 20 or less inches in diameter, with energy yields ranging from less than 1 kiloton (kt) to hundreds of kilotons. The small package size permits a nuclear explosive to be placed more easily and at less cost than chemical explosives with an equal energy yield.

Nuclear explosives may be of the fission or fusion type, and in either case can be constructed to produce within about 20 percent of any desired yield. This permits design of projects with satisfactory safety factors, and fairly reliable prediction of radiation, rock breakage, and seismic motion.

All proposed peaceful uses for nuclear explosives that will be discussed in this paper are based upon either "crater" or "chimney" formation. Both of these features have been well covered by other speakers here. For our purpose we will consider a crater a hole in the ground surrounded by a raised lip, or rim. We will consider a chimney a cylinder or column filled with fragmented rock and completely contained within the earth. Figure I shows the sequence of formation of a nuclear explosive-created chimney, and as shown, radial fracturing accompanies cavity formation. This radial fracturing is an important feature for many proposed Plowshare uses. Figure 2 shows the generally accepted profiles for nuclear crater formation based on depth of explosive burial.

GENERAL PLOWSHARE APPLICATIONS

Plowshare applications, as proposed, fall into two general classes, (I) contained explosions, and (2) cratering explosions. Under the contained classification we might list the following possible uses: (a) Oil and natural gas stimulation; (b) in situ copper (and other mineral) leaching; (c) in situ shale oil production; (d) underground storage facilities for gas, water, waste, and other materials; (e) development of water resources; (f) and other uses. Under the cratering classification we would have a general heading "Excavation," which would include the following: (a) Canal excavation; (b) harbor formation; (c) ore stripping; (d) highway and railroad cuts; (e) production of aggregate for dam construction; (f) construction of slide-dams; and (g) other.

In general, the use of nuclear explosives for the contained type explosion has received more consideration recently than the cratering type explosion because, in the former case, radiation problems are at a minimum and do not come into conflict with current treaties. Let us examine in more detail some of the contained type uses.

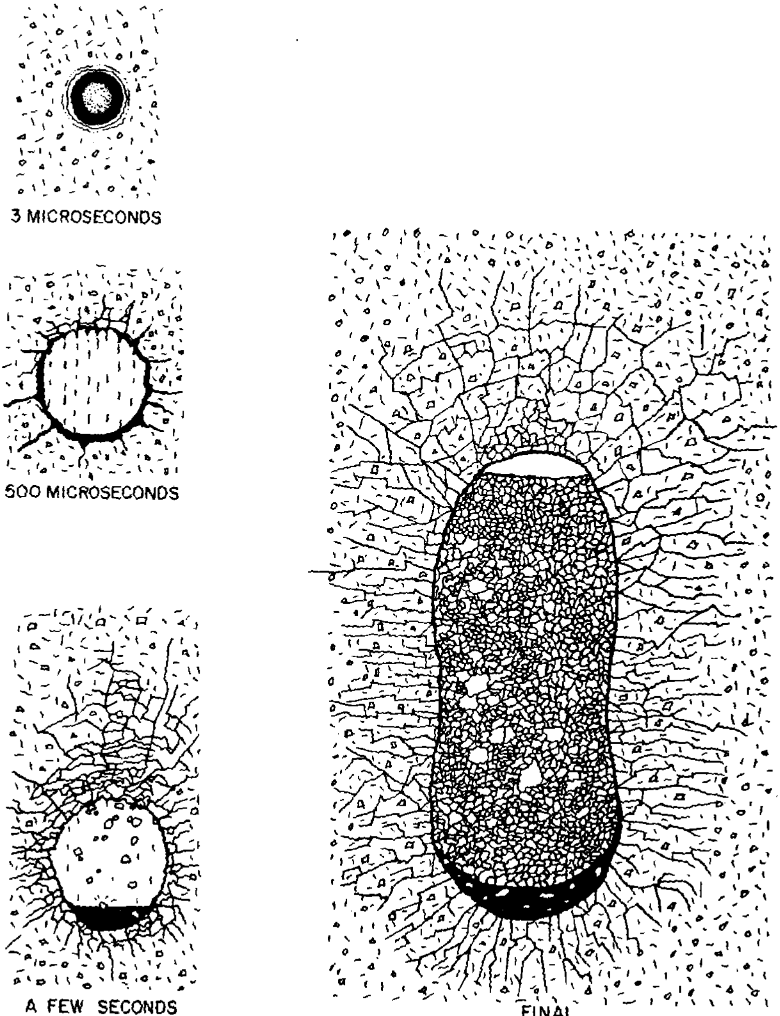
Application to Natural Gas Stimulation

One promising use for an underground nuclear explosion is aimed at stimulating the production of natural gas from low-permeability formations. Currently one experiment is underway, and two others are being planned for the very near future.

Gasbuggy is the Project for an experiment jointly sponsored by the U. S. Government and the El Paso Natural Gas Company. A 26-kt explosive was fired on December 10, 1967, at a depth of 4,200 feet in the Pictured Cliffs gas reservoir near Farmington, New Mexico. This was the first experiment in the use of a nuclear explosive to stimulate gas production. Because this explosion was contained there was no venting of gas or radioactivity.

Evaluation of this experiment is well along, and preliminary results appear quite promising.

Dragon Trail is the Project name for a proposed experiment to be conducted about 17 miles southwest of Rangely, Colorado, using a 40-kt explosive in the Mancos B formation, at a depth of 2,700 feet. Because



3 MICROSECONDS

500 MICROSECONDS

A FEW SECONDS TO A FEW HOURS

FINAL CONFIGURATION

FIGURE 1.–A Typical Sequence Of Events When A Nuclear Explosion Is Detonated Underground.

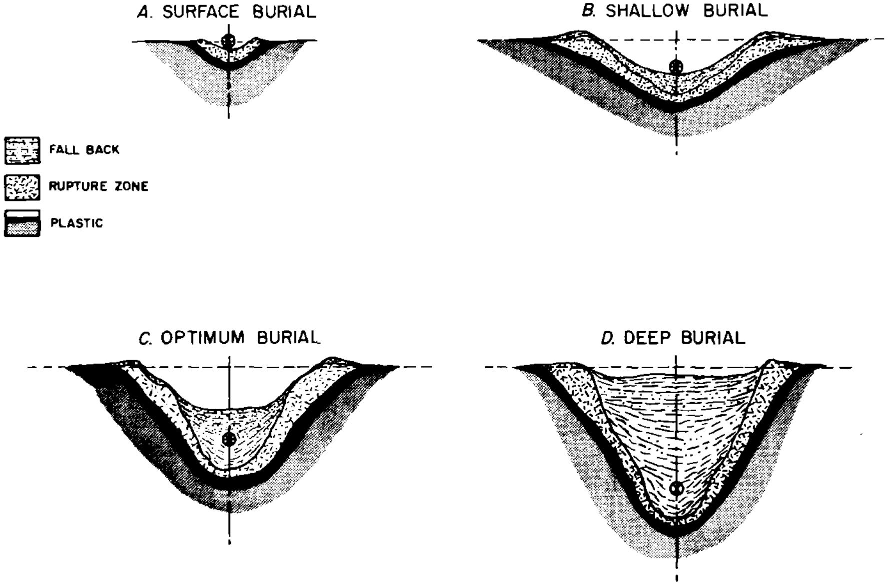


FIGURE 2.–Typical Crater Profiles Versus Depth Of Burst For Alluvium.

the Mancos B is a uniform gas reservoir, the results of this experiment should be of considerable aid in the evaluation of other reservoirs.

Project Rulison, another gas reservoir experiment is proposed for a site in western Colorado, about 13 miles southwest of the town of Rifle. Here a thick interbedded sand and shale formation is estimated to contain over 100 billion cubic feet of natural gas per section.

The ideal results at Rulison would be to produce a chimney 1,600 to 1,700 feet in height to cut the major gas-bearing strata. The initial experiment probably will not produce a chimney of this height, but future experiments would attempt to achieve such a configuration.

If nuclear explosive stimulation is successful, the Rulison field will be highly productive, and a major portion of the gas in place can be produced. More than 100 individual shots of 200 kt each may be needed to fully develop the 60,000-acre holdings of Austral Oil Company. Research will determine whether seismic effects will permit 200-kt production shots.

Pinedale and Wasp are gas-stimulation projects being considered for western Wyoming. For Pinedale, initial studies are underway and actual testing may hinge on the results of Gasbuggy and Rulison, but no planned date for this project has been set. The study of Wasp is in its very early stages and the execution date, if any, is very uncertain.

Application to In Situ Copper Leaching

Leaching is the process of dissolving metal values from an ore, removing the resulting solution from the undissolved materials and extracting the valuable constituents from the solution. Leaching of copper ores was used as early as 2500 B. C., and has become an important method of producing the lower grade of ores today. Roughly 12 percent of domestic production was derived from this method last year.

In situ leaching of ore broken by nuclear explosions has been studied for some time and is considered to present a high potential for use in marginal and submarginal deposits.

Project Sloop is a proposed joing Government-Kennecott Corporation in situ copper leaching experiment, near Safford, Arizona. If successful it would, (1) eliminate the necessity of mining and handling hugh quantities of material, (2) increase the nation's available domestic copper supply by allowing the economic development of copper ore deposits now beyond the scope of current mining techniques and costs, and (3) permit large-scale mining operations with a minimum disturbance to the landscape.

Project Sloop presents a high potential for development of economic uses for nuclear explosives, and at the present rate of progress might be conducted in 12 to 18 months. Commercial development might require detonation of 30 to 50 explosives of 50-kt each if seismic effects permit.

Application to In Situ Shale Oil Production

That a nuclear underground explosion, under given conditions, will produce a chimney of broken rock has been demonstrated in tuff, granite, alluvium, and dolomite. This feature is the basis of a proposed in situ recovery experiment for shale oil production from the vast oil shale deposits of Colorado.

Project Bronco experiment proposed for the Piceance Basin of Colorado would use a 40- to 50-kt explosive to create a chimney of broken shale some 250 or more feet in height. This chimney would then be used as a retort vessel to recover oil by heating the shale in place. The retorted shale oil would be pumped to the surface, and additional treatment would follow for producing gasoline, diesel oil, and other petroleum products.

There has been a great deal of interest in Project Bronco by a group of companies, but the execution of this project seems months in the future. No firm estimate of potential requirements has been made, but if all were to go well, 100 to 300 explosives of over 50-kt might be used.

Application for Underground Storage Space

The concept of using nuclear explosions to produce underground storage space is based upon the chimney formation technique. The open spaces or voids in the broken rock and of the chimney would be used to store gas, oil, water, or waste products.

Project Ketch is an experiment proposed by the Columbia Gas Corporation for the underground storage of natural gas in Pennsylvania. In the planning stage, it involves the detonation of a 24-kt explosive 3,300 feet below the surface in a thick impermeable shale formation. It has been estimated that some 450 million standard cubic feet of gas at 2,100 psi might be stored in the nuclear-produced chimney.

This and similar storage applications appear quite attractive under certain conditions and in certain sections of the United States. It is estimated that between 5 and 25 nuclear shots of this type might occur in the next 10 to 15 years. Yields would vary, but are estimated at about 50-kt each.

Application to Water Resources

Nuclear explosives may prove effective in the very complex problem of water management. The U. S. Geological Survey (6)* states: "Nuclear detonation would be no more than an alternative to conventional engineering means for managing water. Regardless of the means, nuclear or conventional, effectiveness of a management scheme may be limited by a hydrologic feature remote from the principal management works (detonation site). Thus, capability and acceptability of the scheme can be judged only when the whole hydrologic system is known intimately and rather widely."

It is further stated: "Effects of nuclear detonations underground are relatively large in dimension and exceedingly coarse in 'finish'." Such dimension and finish must be in scale with thickness of strata and other dimensions of the natural environment. Precise fitting of detonation effects to minute dimensions of the environment is impossible. Principal side effects of detonations--air blast (if any), ground motion, and both prompt and residual radiations--must be of acceptable intensity lest nuclear detonation be socially or politically impracticable!

Project Aquarius is a joint U. S. Government-State of Arizona study of nuclear explosives for water management. The project has not reached the scheduling stage.

Use of nuclear explosives for water management is indefinite, but it would appear that from 1 to 5 experiments may be performed during the next 5 to 10 years. Further use is dependent on success of these experiments.

Application to Excavation

Of the many potential applications of nuclear explosives, excavation is perhaps the most obvious. Some broad uses proposed are mining, removal of overburden, quarrying, recharge of aquifers and waste disposal, storage of fluids, harbor excavation, canal excavation, flood control, highway and railroad cuts, and slide dams.

Several of these proposals have received serious consideration and study; others are in a very preliminary planning and consideration stage. I will very briefly review those that have attracted the most attention.

Canal Excavation

Much engineering effort has been directed toward determining the feasibility of constructing canals by nuclear cratering. The concept has been demonstrated on a small scale and appears feasible. The future uses for excavation of a trans-isthmus canal is being studied

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*Underlined number in parentheses refer to items in the bibliography at the end of this report.

and involves a great number of factors, including the current Test Ban Treaty, radiation, air blast, and seismic shock. A decision is not apt to be reached in the immediate future, but research continues and results look very promising.

Highway and Railroad Cuts

This type of excavation which parallels canal excavation research was the subject of a joint study by the Sante Fe Railroad and the California Highway Department. The principle of application appears feasible and needs only the proper site and economic condition for possible use.

Harbor Excavation

Here again the principles involved are basically the same as for canal or surface cut excavation. Harbor excavation (Project Chariot) was studied for Alaska and is currently of high interest in Australia. A test excavation might be made in a year or two, but future use appears very limited.

Overburden Removal

Overburden covering an ore deposit might be removed by either single or multiple cratering blasts. This use has been studied and, as expected, such use is rather limited in the rather densely populated United States but may be more favorable in some less densely populated foreign areas.

Recharge of Aquifers and Waste Disposal

Either a crater or chimney would be excavated by nuclear explosives in a favorable geologic formation to which surface water or waste could be channeled for storage. This is a potential use that needs more study.

Flood Control and Storage of Fluids

For this use either a thowout crater or subsidence crater produced by nuclear explosives might be used to catch flood water or store liquids. This potential usage does not appear economic and its early use is doubtful.

Quarrying and/or Slide Dams

For this application a nuclear explosive would be used to break large quantities of rock. If the rock were confined to a canyon or stream bed it might create a useful dam. Both uses have been considered for dam construction.

All of the above proposed uses are somewhat limited at present by the Test Ban Treaty. For those not familiar with this Treaty, it basically states that all radiation produced from testing must be kept within the boundaries of the country conducting the test. Because nuclear explosions of the excavation type produce radiation as well as air blast and seismic shock, areas for use appear somewhat limited. With this in mind, it is not expected that a rapid growth of nuclear explosive excavation will take place. Unless a sea-level canal is cut, total excavation type blasts should number less than 10 during the next five years.

PROBLEMS IN USE OF NUCLEAR EXPLOSIVES

There are a number of hazards that must be considered where nuclear explosives are planned. Because the purpose of this symposium is to explore many of these in detail, I will mention only the major hazards--radiation, air blast, and ground shock--which we might look at in a little more detail.

Ground Shock

In many cases the most serious problem encountered in the use of nuclear explosives may be the seismic wave. A large part of the energy of both contained and cratering explosions is carried off by the shock wave, which travels outward from the explosion point, losing energy by heating, crushing, and deforming the rock. Eventually the shock pressures fall below the elastic limit of the medium and become an elastic wave. As this elastic wave spreads concentrically, its amplitude decreases rapidly with distance. When the wave reaches structures or other habitation, it may cause cracking of plaster or other damage if the particle velocity is high enough. Since buildings and other structures themselves are elastic, they may respond to the seismic wave as free oscillators and amplify or reject the motion of the ground. In general, the larger the explosion, the further away we may expect buildings and other damage to occur.

Radiation

Seeing that radiation in its numerous forms and effects are major items of this symposium, I would be foolish to do more than touch upon the subject.

There are two sources of radioactivity from an underground nuclear explosion. One is the direct products of the nuclear reactions (fission products and tritium). The second is the radionuclides induced in the surrounding media by the neutrons that are explosion byproducts. Where the explosion is contained, little if any of the radioactivity escapes to the atmosphere. In the case of cratering explosions, considerable radioactivity may be vented. In either case, a great deal is known about all aspects of the radiation problem, and continued research is producing cleaner nuclear explosions. Thus, the future for Plowshare looks promising.

Air Blast

Air blast may be a serious problem in some cratering shots. The hot gasses vented at extreme pressure may cause a high velocity blast wave. As this blast wave traverses structures, the resulting difference in air pressure, acting on the separate surfaces, produces forces that can cause structural damage. In addition to static pressures, there are dynamic pressures resulting from the air movement accompanying the passage of the blast wave.

As the blast wave travels away from its source, the over-pressure at the front steadily decreases and the pressure behind the front falls off in a regular manner. As this progresses, structures or persons in the vicinity experience first an over-pressure and then an under-pressure. Obviously, the safety criteria used for a particular project will depend on the area involved.

ECONOMICS OF NUCLEAR EXPLOSIVE USE

Although there may be a few cases in which costs are not important, these will be rare indeed. There are several basic major cost items involved in the use of nuclear explosives: Device and emplacement costs; fielding costs, including safety; and hole-size and device requirements. More emphasis on the economics of individual projects will have to be developed as commercial uses for nuclear explosives expand.

TIME SCHEDULE OF FUTURE USE

Nuclear explosives will be used commercially only if they show economic advantages over conventional explosives. To date we have no such demonstrated application, which means that nuclear explosions will be of a research nature with immediate use limited to probably less than 5 per year. This rate of use should continue for from 2 to 5 years. Within 5 years, it is estimated that research and testing in natural gas stimulation and copper leaching will indicate economic feasibility. If such is the case, the use of nuclear explosives may expand to 10 to 30 per year. This rate should grow during the coming years (especially in gas stimulation) to possibly 100 or more explosions per year. Growth in other areas is dependent on successful test programs that are expected to develop rather slowly. There is the potential for a few "one-shot" type uses developing within the next 10 years, which may include harbors and canals and overburden removal and water management.

It is expected that commercial use of cratering-type explosions will grow very slowly and under strict limitations. Non-cratering or contained explosions offer the earliest and potentially the largest field for future nuclear explosive application.

CONCLUSION

I have very briefly listed and discussed those nuclear explosive research projects now being conducted or planned for future consideration. I have attempted to evaluate these to some extent and to estimate the growth of nuclear explosive use for the next few years. This projection of future use is only my own estimate; I am sure some feel that the growth will be much more rapid, while others will feel I am overly optimistic. Only time will permit an evaluation of our opinions. However, I again state that I feel future use depends on demonstration of economic feasibility. Growth in use will be rather slow and, to some extent, will be based on development of capabilities to field such use.

REFERENCES

1. Coffer, H. F., H. E. Grier, and H. H. Aronson. The Use of Nuclear Explosives in Oil and Gas Production. Proceedings World Petroleum Congress, 1967, 21 pp.

2. Coffer, H. F., G. H. Higgins. *Nuclear Explosives for Oil and Gas* Stimulation and Shale Oil Recovery. Pres. at the Southwestern Legal Foundation's Eighth Annual Institute on Exploration and Economics of the Petroleum Industry, March 6-8, 1968, 35 pp.

3. Coffer, H. F., and E. R. Spiess. Commercial Application of Nuclear Explosives--The Answer to Oil Shale? Pres. at Third Annual Oil Shale Symposium, Denver, Colorado, April 14-15, 1966, 12 pp.

4. "Excavation" Part II of the Proceedings of the Second Plowshare Symposium, Lawrence Radiation Laboratory (Livermore), UCRL-5676, May 1959.

5. Kruger, Paul. Nuclear Civil Engineering. TID-23748 Atomic Energy Commission, 1966, 329 pp.

6. Piper, Arthur M. Potential Application of Nuclear Explosives in Development and Management of Water Resources--Preliminary Canvass of the Ground-Water Environment. TEI-873, Atomic Energy Commission, 1968, 173 pp.

7. Ward, D. C. and C. H. Atkinson. Project Gasbuggy--A Nuclear Fracturing Experiment. Society of Petroleum Engineers of AIME, SPE-1273.

8. Wilson, A. R. W., E. B. Pender, and E. K. Carter. An Evaluation for Australian Purposes of Proposed Civil Engineering and Mining Applications. TID-4500 Atomic Energy Commission, 1964, 219 pp.

APPROACHES TO THE CALCULATION OF LIMITATIONS ON NUCLEAR DETONATIONS FOR PEACEFUL PURPOSES*

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ABSTRACT

The long-term equilibrium levels of tritium, krypton-85 and carbon-14 which are acceptable in the environment have been estimated on the following premises: 1) the three isotopes reach the environment and equilibrate throughout it in periods shorter than their half lives, 2) nuclear detonations and nuclear power constitute the dominant sources of these isotopes, 3) the doses from these three isotopes add to one another and to the doses from other radioactive isotopes released to the environment, and 4) the United States, by virtue of its population, is entitled to 6% of the world's capacity to accept radioactive wastes.

These premises lead to the conclusion that U.S. nuclear detonations are limited by carbon-14 to 60 megatons per year. The corresponding limit for U.S. nuclear power appears to be set by krypton-85 at 100,000 electrical megawatts, although data for carbon-14 production by nuclear power are not available.

It is noted that if the equilibration assumed in these estimates does not occur, the limits will in general be lower than those given above.

INTRODUCTION

This paper presents the results of some calculations of three radioactive isotopes produced and, in present practice, released to the environment by nuclear explosions and by the production of nuclear power. The three isotopes are tritium (hydrogen-3), krypton-85 and carbon-14. These, among the

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*The work reported here was performed under the auspices of the U.S. Atomic Energy Commission while the author was a summer visitor at the Lawrence Radiation Laboratory, Livermore, California.

long-lived radioactive isotopes produced in nuclear fission and fusion, are the most likely to disperse throughout the environment. There are few physical, chemical, or biological mechanisms which tend to concentrate these isotopes within any phase of the environment.

THE PREMISES

The first step is the calculation of the steady state concentration limit for each of the three radioisotopes. The calculations are founded on three assumptions.

1. All of each of the three radioisotopes is released to the environment in a time shorter than its radioactive half life.

2. Each of these isotopes equilibrates with the corresponding stable isotope, which is available in the environment, in a time shorter than half life.

3. The quantities of stable isotopes in the environment available to dilute the corresponding radioactive isotopes are those given in the last column of Table 1.

It is to be noted in Table 1 that the hydrogen in the water of ice and sediments has been taken to be unavailable for dilution and that only one-tenth of the hydrogen in the water of the oceans is presumed to be available for dilution. Only the hydrogen in land organisms and one-tenth of that in sea organisms has been taken to be available for dilution. The carbon in undecayed organic matter and in coal, oil, tar and gas has been neglected, and only one-tenth of that in the oceans and in sea organisms has been taken as available for dilution.

RADIOLOGICAL CONSIDERATIONS

The maximum dose considered permissible for a person other than a radiation worker is 0.5 rem per year (2). Table 2 gives the specific activities (μCi per gram of stable isotope) which will produce 0.5 rem per year by several routes of exposure: 1) breathing, or in the case of krypton-85, standing in an atmosphere at the maximum permissible concentration, 2) drinking water at the maximum permissible concentration, 3) eating food that will produce the maximum permissible daily intake, and 4) having the maximum permissible body burden in one's body. Table 2 indicates that the limiting specific activities for tritium and carbon-14 are those in the body itself, while that for krypton-85 is set by air.

Table 1. The quantities of hydrogen, krypton and carbon available in the world for dilution.

Hydrogen in:	Total (1)	Assumed to be available for dilution
Oceans	1.6×10^{23}g	1.6×10^{22}g
Lakes and rivers	5.5×10^{19}g	5.5×10^{19}g
Ice	2.4×10^{21}g	-
Atmosphere	1.4×10^{18}g	1.4×10^{18}g
Sediments	2.2×10^{22}g	-
Organic material	4.0×10^{18}g	7.0×10^{16}g
Total		1.6×10^{22}g
Krypton		
Volume of the atmosphere (at 0°C, 760 mm)	4.3×10^{24}cc	-
G of krypton per cc of air	4.3×10^{-9}g/cc	-
Krypton in the atmosphere	1.8×10^{16}g	1.8×10^{16}g
Carbon in:		
Troposphere	5.5×10^{17}g	5.5×10^{17}g
Oceans	4.0×10^{19}g	4.0×10^{18}g
Lakes and rivers	3.2×10^{17}g	3.2×10^{17}g
Land organisms	1.0×10^{17}g	1.0×10^{17}g
Sea organisms	8.0×10^{16}g	8.0×10^{15}g
Undecayed organic matter	3.9×10^{18}g	-
Coal, oil, tar, gas	7.4×10^{18}g	-
Total		5.0×10^{18}g

Table 2. Bases for the calculation of annual replacement rates.

		Units	H-3	Kr-85	C-14
1.	Radioactive half life	years	12.3	10.4	5,600
2.	Max. perm. body burden (3)	µCi	100.	-	30
3.	MPC* in public air (2)	µCi/cc	2×10^{-7}	3×10^{-7}	1×10^{-7}
4.	MPC* in drinking water (2)	µCi/cc	3×10^{-3}	-	8×10^{-4}
5.	Max. daily intake in water (2)	µCi/day	7.	-	2.
Specific activity** limit set by:					
6.	Breathing	µCi/g	0.6	70.	1.
7.	Drinking water	µCi/g	0.3	-	1.
8.	Eating food	µCi/g	0.2	-	0.005
9.	Max. perm. body burden	µCi/g	0.01	-	0.002
10.	Limiting specific activity	µCi/g	0.01	70.	0.002
11.	World capacity at the limiting specific activity	Ci	2×10^{14}	1×10^{12}	1×10^{10}
12.	Annual replacement rate	Ci/year	1×10^{13}	7×10^{10}	1×10^{6}

Notes

*MPC stands for maximum permissible concentration.

**Specific activities are in µCi per gram of stable element.

Row 10 of Table 2 gives the limiting specific activity for each of the three radioisotopes, i.e. the specific activity of each isotope which will deliver an average radiation dose of 0.5 rem per year to every person in the world. These specific activities, with the corresponding stable isotopes available for dilution given in Table 1, permit one to calculate the world capacity for each radioisotope; these world capacities are given in row 11 of Table 2.

Each of the three radioisotopes decays with a characteristic radioactive half life. Thus there is for each isotope an annual replacement rate which will just maintain the world environment at the limiting specific activity. These annual replacement rates are given in row 12 of Table 2.

The figures in the last three rows of Table 2 are not suitable limits for two reasons. First, these figures make no allowance for the differences between the calculated predictions for an average individual in the population, and the actual exposure received by any particular individual. The Federal Radiation Council (4) and the U.S. Atomic Energy Commission (2) have both stipulated a factor of 1/3 for this purpose.

The second reason why the world capacity figures in Table 2 are not suitable limits is that they make no allowance for the summing of the doses from the three radioisotopes, from all other man-made radioisotopes in the environment, or from other man-made sources of radiation. The intent is that "persons in the general population at any age... should not receive an exposure exceeding 0.5 rem per year in addition to natural background and medical exposures."(5). In order to allow for the summing of doses from various radioisotopes and other sources of radiation a factor of 1/10 is appropriate.

ALLOCATION

In considering the long pull, one must face the matter of allocation: to how much of the world's capacity is each geographical unit entitled? To what portion of this share is each nuclear undertaking entitled?

The United States constitutes about 7% of the world's surface and in 1966 had about 6% of the world's population (6). On the other hand the United States is at present using about 30% of the world's energy (7). If the principle of one man, one vote is extended to one man, one polluter, the United States' allocation is about 6% of the world's capacity to accept radioactive wastes.

Nuclear explosives (fission and fusion) and nuclear power (fission) are today the dominant sources of the three radioisotopes considered in this paper. Whether an equal share of the available capacity is to be allotted to each of these undertakings, or whether more of the capacity goes to one than the other is a matter to be decided on the relative importance of explosions and power. As an illustration, but surely not as a recommendation, the following calculations have been made by allocating a half of the U.S. capacity to nuclear explosions, a half to nuclear power.

Table 3 summarizes the radiological and allocational considerations, and indicates that about 1/1000 of the replacement rates in the last row of Table 2 is appropriate for U.S. nuclear explosions, and an equal amount for U.S. nuclear power.

PRODUCTION OF THE THREE RADIOISOTOPES

The production of the three isotopes under consideration by nuclear explosions is a function of several factors: a) the fission to fusion ratio, b) the atomic composition of the explosive device and its associated equipment, c) the composition of any neutron shield that is used, and d) the composition of the soil in which the explosive is detonated. These factors may be manipulated for engineering purposes, and are, further, veiled by security classification. The estimates for the production of the three isotopes by nuclear explosives have been based on the declassified information in the upper portion of Table 4.

The corresponding production figures for tritium and krypton-85 are given in the lower portion of Table 4. Note that no figures for the production of carbon-14 by nuclear power appear in Table 4. Such production certainly occurs by neutron capture in nitrogen whenever air and neutrons get together, but no estimates of production rates appear to have been made.

Tritium may be produced in nuclear reactors by neutron capture in hydrogen-2 and in lithium-6. It has been estimated that the amounts of tritium produced by these reactions in power reactors may perhaps equal the tritium produced by fission (13). As a consequence, the tritium production figure in Table 4 should be increased from 14 to perhaps 30 Ci per electrical megawatt-year.

Table 3. Summary of considerations.

	Factor
Radiological	
Individual variation from the average	1/3
Summing of doses from various isotopes	1/10
Allocation	
United States' share of world capacity	0.06
Share allotted to nuclear explosions (an equal share is allotted to nuclear power)	1/2
combined factor	0.001

Table 4. Production rates of the three radioisotopes.

Nuclear explosives

fission to fusion ratio (8)	10 kt fission for 1 Mt fusion
10 kt of fission (9)	$1.46x10^{24}$ fissions
krypton-85 fission yield (10)	$2.93x10^{-3}$ per fission
krypton-85 production	290 Ci per 10 kt fission, i.e. per 1 Mt fusion
tritium production (8,9)	$1x10^{7}$ Ci per Mt fusion
carbon-14 production(8)	15 Ci per Mt fusion

Nuclear power

electrical to thermal ratio	1 Mw(e) for 3 Mw(t)
1 Mw(e) for 1 year (11)	$9.86x10^{23}$ fissions
krypton-85 fission yield (10)	$2.93x10^{-3}$ per fission
krypton-85 production	480 Ci per Mw(e) in 1 year
tritium fission yield (12)	$9.5x10^{-5}$ per fission
tritium production	14 Ci per Mw(e) in 1 year

LIMITS ON NUCLEAR EXPLOSIVES AND NUCLEAR POWER

In Table 5 the production figures developed in Table 4 for tritium, krypton-85 and carbon-14 have been used to determine the limits imposed on nuclear explosives and nuclear power by 1/1000 of the world replacement rates, given in Table 2. It is evident from Table 5 that the limit on U.S. nuclear explosions is set by carbon-14 at about 70 megatons per year and that U.S. nuclear power is limited by krypton-85 to about 150,000 electrical megawatts.

DISCUSSION

Under the idealized conditions used in these calculations, 90% of the final equilibrium specific activities will be reached in about three half-lives, say 35 years for tritium and krypton-85, and 20,000 years for carbon-14. It is possible to release more than the equilibrium rates in some years, but such averages must be compensated by releasing less than the equilibrium rates in other years. This is analogous to buying on credit and does not violate the Atomic Energy Commission requirement that exposures may be averaged over periods no longer than one year (2), provided the limiting specific activities are not exceeded.

The premise that the three isotopes are released to the environment in periods shorter than their half-lives should be questioned. If it can be shown, or if it can be arranged that 90% of the limiting isotope can be restrained from entering the environment for three or more half-lives, the limiting rates in Table 5 may be increased by a factor of ten.

The premise that the three radioisotopes equilibrate throughout the environment in periods shorter than their half-lives is tenuous. However, to the extent that equilibrium is not established, specific activities will be higher in some locations than would be the case in complete equilibrium. If the portions of the environment that are at higher than equilibrium specific activities lie on human food pathways, then limits lower than those in Table 5 must be used.

The factors used to allow for individual variations from the average, for the summing of doses, and for rationing may be considered as conservative safety factors. Safety and conservatism receive great, perhaps undue emphasis in radiation. However, in considerations of the environment, it is wise to set aside certain portions to lie fallow for future and unforeseen needs.

Table 5. Limits on nuclear explosions and nuclear power for the United States.

	H-3	Kr-85	C-14
World annual replacement rate, Ci/year (from Table 2, row 12)	1×10^{13}	7×10^{10}	1×10^{6}
The United States' share for nuclear explosives, or power, Ci/year (see Table 3)	1×10^{10}	7×10^{7}	1×10^{3}
Limit imposed on nuclear explosives, Mt/year	1,000	240,000	67
Limit imposed on nuclear power, Mw(e)	7×10^{8}	150,000	-

The concept of balancing risks against benefits has been worked very hard, perhaps to exhaustion, in radiation protection. In the present context this concept leads to two questions of singular subtlety: risks to whom? benefits to whom?

CONCLUSIONS

The deliberations presented here lead to the conclusions that *on the long view U.S. nuclear detonations are limited* by carbon-14 to an average rate of 70 megatons per year, and that the corresponding limit for U.S. nuclear power appears to be set by krypton-85 at 150,000 electrical megawatts. These limits can be raised if means are devised to prevent the escape of the limiting radioisotopes to the environment.

REFERENCES

1. A. Poldervaart, ed. *Crust of the Earth,* Geological Society of America, New York, p. 121-123, 1955.
2. U.S. Atomic Energy Commission Rules and Regulations, 10CFR20.
3. International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, Health Physics *3*:1, 1960.
4. Federal Radiation Council, Background Material for the Development of Radiation Protection Standards, Report No. 1, p. 30, May 13, 1960.
5. National Council on Radiation Protection and Measurements, Radiation Protection in Educational Institutions, NCRP Report No. 32, p. 7, July 1, 1966.
6. L. H. Long, ed. *World Almanac,* Newspaper Enterprise Association, New York, 1968.
7. P. C. Putnam, *Energy in the Future,* Van Nostran, New York, 1953.
8. F. W. Stead, p. 128 in Engineering with Nuclear Explosives, TID-7695, 1964.
9. J. A. Miskel, p. 153 in Engineering with Nuclear Explosives, TID-7695, 1964.
10. American Institute of Physics Handbook, 2nd ed, p. 8-225.
11. Atomic Energy Desk Book, p. 353, Rheinhold, 1963.
12. E. L. Albenesius and R. S. Ondrejein, Nucleonics *18*: No. 9, p. 100, 1960.
13. J. E. Blomeke, F. E. Harrington, Management of Radioactive Wastes at Nuclear Power Stations, ORNL-4070, January 1968.

QUESTIONS FOR HOYT WHIPPLE

1. From Alex Grendon:

Did you take into account the annual production of carbon-14 and tritium by cosmic radiation? Do you know if these amounts are significant in relation to potential production by man's activities?

ANSWER:

I do not have the figures with me, but the natural production rates of these two isotopes, as I recall, are small, very small fractions of the rates that I have been speaking about here and I think if you do a little simple arithmetic, you'll help me gain confidence in this statement, which is based on a poor memory, which said that the particular release rate which is one thousandth of the release rate that would ultimately lead to 0.5 rem per year would lead to 0.5 of a millirem per year from the United States alone. There may be someone in the room who remembers the breakdown well enough, but as I recall, carbon-14 and tritium from natural causes constitute a very small part of the natural background exposure.

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ROLE OF INDUSTRY IN THE ENVIRONMENTAL HEALTH AND SAFETY ASPECTS OF THE DEVELOPING PLOWSHARE INDUSTRY

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ABSTRACT

It is first pointed out that no person or organization has a more vital interest in the early establishment of an effective health and safety program within which commercial operations based on Plowshare technology can be carried on with assurance than does that facet of industry which is directly involved in the attempt to prove out these Plowshare applications. The formulation of such a code must be a matter of the highest priority to all concerned.

To accomplish this task successfully, however, requires the exercise of a truly hard-nosed objectivity both on the part of the Governmental agencies who bear statutory responsibility for ensuring the public health and safety and also on that of the industrial groups who are trying to realize the significant economic potentials inherent in the Plowshare technology. While it is abundantly clear that achievement of a sound and reliable public health and safety code is imperative for both regulatory agencies and operating industry, it must also be recognized that both groups serve the inescapable additional responsibility of acting as the public's trustees to assure the healthy development of a new technology which may well prove to be of vital importance to the Nation. The basic nature of the joint operating procedure required in order to provide an effective way of fulfilling these common obligations is then examined.

The discussion then turns to the present stage of the developmental progress of the potential Plowshare industry. Scientific breakthrough has long since been accomplished and scientific feasibility has been quite generally proven. For a number of important possible applications even technological feasibility has been established. In these cases the demonstration of economic feasibility and the attainment of public acceptance are the two factors that still remain to be achieved before a full-fledged

if still infant industry becomes a reality. Industry alone is capable of determining economic feasibility. It is also upon industry that the primary responsibility for gaining public acceptance will fall and with all other factors "go" it will be this latter factor, the public's willingness not only to tolerate but actually to "buy," that will determine whether there is to be a business or not.

Whether or not any proposed commercial application will prove to be economically feasible and whether or not public acceptance can be achieved will depend critically on the nature of the essential health and safety activities required and on the associated costs of these activities. For industry to proceed with effectiveness, three immediate measures are particularly needed.

First, a tentative, "best-as-of-the-moment" health and safety code covering operational procedures and end product specifications should be formulated to serve as a test set of rules for immediate field use and as a concrete, "point-of-departure" statement in the development of the eventual regulatory code. The upcoming technological feasibility tests in the Plowshare program should then be used to evaluate its commercial applicability and to guide its evolution toward regulatory status. Here joint action is obviously imperative.

Next, if the foregoing is to be meaningful, the research and development aspects of these upcoming tests with respect to health and safety, important as they are, must be scrupulously separated, at least costwise, from the necessary health and safety operational activities as specified in the provisional code. No matter how cogent, considerations of budgetary expedience must not be permitted to intervene either within the Governmental agencies or within the participating industrial organizations. Honest, "unloaded" operating costs are an absolute must if the tests themselves are to be meaningful.

Finally, it must be recognized that time is one of the most significant factors in determining the success or failure of any industrial endeavor. The present case is no exception. The time factor must be kept continually in mind, for delay can spell defeat for a commercial activity just as surely as can technological failure. Whenever a contemplated course of action will impose delay, it is vitally important that the anticipated advantages be weighed meticulously against the possible detriments lest the hope of small gains inadvertently lead to the achievement of total ruin. Here again the truly judicial sort of appraisal *required can be realized only to the extent that open communication and joint evaluation procedures can be established.*

Success in implementing the required joint operations with due regard to individual responsibilities is anticiapted.

* *

Mr. Chairman, Fellow Panelists, Colleagues. I am particularly happy to have the privilege of being a member of this panel discussion and this on two distinctly different counts. In the first place, having not only officiated at the birth of the nuclear energy health, safety, and bio-medical research programs but also having nursed them around the clock for their first twenty years, attending this symposium is very much like coming back to a family reunion to see how the children and grandchildren are doing.

In the second place, I feel highly complimented by my industrial colleagues to be asked by them to present this discussion of the nature of industrial responsibilities in the area of environmental health and safety. My position as university professor and ex-National Laboratory director speaking in behalf of industry is not quite as anomalous as it might appear at first sight since I have served on the Board of Directors of the Atomic Industrial Forum for the past seven years. Thus what I have to say reflects this latter experience fully as much as it does the former.

Before proceeding to my discussion of industry's role in environmental health and safety, I would like to make one point emphatically clear. Nowhere during my long career in the nuclear field have I found a more deep-seated respect for a fully effective health and safety program than I observe everywhere within the nuclear industry. I realize that in these days it probably verges on the immoral to suggest that any segment of industry is indeed actively safety conscious. I am convinced, nonetheless, that no individual or group is more keenly and more completely concerned with achieving a totally safe operation than is the nuclear industry. A major segment of this industry's top management has come up through the nuclear laboratories and nuclear energy production facilities where traditionally an acute consciousness of the need to monitor every conceivable source of potential trouble and to do so ceaselessly is bred into the very marrow of their bones. No one is more aware than they that the one nuclear accident that we can never tolerate is the first. True, although all of us are vitally concerned with the overall nuclear health and safety program, each of us must perforce operate within quite different areas of responsibility and thus may differ amongst ourselves concerning the most suitable ways of achieving the goal of a totally safe operation. With respect to the nature of the goal, however, and to the necessity for attaining it, there exist no differences at all - we all share a common conviction. Indeed from the industrial point of view, unless that goal can be effectively achieved, there can be no significant nuclear industry. It is for this reason that that facet of industry which is directly involved in attempts to prove out the industrial feasibility of economically promising Plowshare applications is vitally concerned with the early establishment of an effective health and safety code within which commercial operations based on Plowshare technology can be carried on with assurance. Such a code is in a real sense the legal skeleton upon which the operating musculature of sound safety practice can be fixed. Such a code will not spring full formed from the waves. It must evolve, but it can do so only if some primeval form exists from which a logical evolution can follow. The formulation of this elemental safety structure must be our first order of business and a matter of the highest priority to all concerned.

Now it is quite clear that the statutory responsibility for generating this essential tentative code, for developing it through its evolutionary stages to full regulatory status and for its enforcement when established, must lie with the government agencies. With the very considerable body of data already available both in the fields of blast phenomena and of radiation effects, one might question why the first steps toward such a code have not already been taken. The answer to that to produce even a wholly tentative and purposely elemental code is not so simple as it might appear. Permit me to illustrate with an example from our national nuclear history.

I had the privilege of living right at the center of the first case of the development of nuclear safety requirements. That was in connection with the design of the X-10 nuclear reactor at what is now Oak Ridge National Laboratory, with that of the Hanford production reactors at Richland, Washington, and with the design of the chemical processing facilities at both locations. The need for radiation safety guidance was first propounded in emphatic fashion by the physicists at the Metallurgical Lab as early as March or early April 1942 and was seconded by the chemists shortly thereafter. Prior to that, in early February 1942, a medical examination program, with radiation effects constituting a principal objective, had already been established at the Laboratory. Following this, a radiation monitoring organization was set up during February and March, and an instrument division was organized to design and produce the necessary monitoring devices. When the full impact of the radiation problems inherent in nuclear reactors was recognized, a Health Division was established in April which included the existing medical examination and radiation monitoring activities and which also initiated intensive medical and biological research programs in radiation effects on living systems and in the toxicology of the radioactive and other esoteric materials with which we were dealing.

The first order of business of this Health Division was to come up with a statement on reactor shielding requirements since the X-10 reactor was already in the design stage. It was fortunate that the reactor physicists, the reactor engineers, and the bio-medical personnel had to live together. With only the sketchiest of data available and with their own early experiments indicating that those prior data were in some instances suspect, the bio-medical staff did the normal, to-be-expected thing. They looked at the data and decided on what that raw data would indicate a safe "permissible level" to be. Then on the basis of the general state of experimental statistics in biological investigations, they introduced a safety factor of ten. Since the data in this case were at least partially suspect, they tossed in a tentative additional factor of ten. Finally, since no accident could be tolerated, not only on the basis of the value of the human lives that might be directly involved but also because an accident could breach the military secrecy and thus endanger the entire National security, they decided to really play it safe and put in another factor of ten or so. Here was where juxtaposition of personnel paid off, for when the bio-med personnel announced their permissive dose specification, the physicists and in particular the engineers nearly exploded. There were comments that the proposed exposure level was far lower than the level of cosmic rays to which man is exposed during his lifetime. This blast didn't seem to shake the life scientists too much. However, when they saw the engineers' figures on what their proposed level was going to mean in the thickness of the shielding that would be required to achieve an attenuation of the reactor radiation down to their stipulated level, they were shaken. It was a sort of "fill-all-space-with-concrete-leaving-a-small-hole-in-the-middle-for-the-reactor" deal. At this point, the hard-nosed give-and-take of arguing out a fully safe but practicably achievable reactor shielding design got under way, and in due course a suitable design was achieved. True, the bio-medical staff did retreat from their original extreme position, but they did so without compromising the real safety of the reactor. What they did do was to trim some of the "super-super" factors they had put in. These had been introduced not because of requirements implied in the available data or even the known uncertainties in the data, but because of that very basic human reaction that, if safe is safe, doubly safe must per se be better - a sort of inverse "over-kill" philosophy.

Now I suspect that I have overstated somewhat the exact values of the safety factors that were actually involved in this case, but I have not overstated the case itself in the slightest in terms of the operational philosophy it portrays. The project never could have met its schedules had it not been for the intimate, hard-nosed give-and-take between the reactor designers who, to the best of our belief at the time, held the Nation's military survival in their hands, and the bio-medical personnel who we held responsible for the health and safety both of the future reactor operators and of the civilian population who could conceivably suffer serious damage by faulty design. The outcome of that dialogue was that each group, under the spur of the other, exercised a degree of critical evaluation of their own scientific and technological positions that it would have been essentially impossible to have achieved otherwise. They arrived at the solution both demanded -

full safety - and they arrived at that solution while keeping within the bounds of technological and economic feasibility.

The situation we face today, in its basic managerial aspects, is strikingly similar. The compulsory physical juxtaposition of the different concerned groups within a single organizational structure is absent, and the dramatic, driving sense of urgency obviously does not obtain. Otherwise, the two situations have much in common. For example, there can be no question but that both the government agencies and the Plowshare industries involved share the firm conviction that a fully safe operation is imperative; the agencies are under statutory requirement to ensure it, and the industry cannot endure without it. I would also say that while the present state of scientific and technological data within the nuclear business is enormously improved over that existing in 1942, nonetheless the data in the Plowshare field are sufficiently inadequate to tempt anyone devising a safety code to adopt the "doubly safe" philosophy until strongly persuaded by circumstance to do otherwise. Finally, it is also true that here as well as in the historical instance, the bio-medical fraternity which must necessarily constitute the core of the governmental agencies involved are not only explicitly charged by statute with responsibility for essentially guaranteeing the public health and safety, but implicitly, by the very existence of the statute under which they operate, they are also made joint trustees of the public interest in the attainment of the benefits which successful exploitation of the field might yield. Had it been otherwise, the statute would simply have prohibited the potential applications a much simpler solution than strangling the cat with the hot butter of a body of prohibitive health and safety regulations. It seems to me that we face much the same situation we did twenty-seven years ago, and I believe that the same basic motivations exist on the part of the regulators and the regulated. Today both groups require a fully safe operation and, even though their reasons for so doing may be quite different, this in no way alters the identity of their joint purpose. Again both are concerned with the achievement of a technological and industrial goal, one that could prove to be of vital import to the nation as a whole. The significantly augmented national reserves of proven recoverable natural resources available to our economy without recourse to transport outside the protection of our geographic boundaries which could result from a successful Plowshare enterprise and the impact of this altered domestic situation on our international relationships and policies provides one case in point. The present Plowshare stakes may lack the urgent crisis character of the wartime case but, if evaluated for the long run, they could eventually prove to be of equally vast national significance.

In one area, however, the differences are marked. In a regulatory society any scientific and technological cohabitation between regulators and the regulated may indeed be deemed far more immoral than are certain more generally practised varieties of the act. Be that as it may and as difficult as it obviously may prove to be to achieve, we must find a means of generating a true government agency - Plowshare industry dialogue - if we are to be successful in the enterprise on which we are all engaged. All the government agencies involved must know and really understand the full industrial implications of the measures they propose. On the other hand, industry must know how safe is safe. In their eyes it could turn out not to be safe enough. Industry must also know precisely upon what safety depends, on an across-the-board basis, and fully understand in what way, because only thus can regulation be translated into rational operating procedure. The immediate and urgent problem is that of establishing such an effective dialogue. In my view this meeting constitutes a useful first step. More meetings with perhaps a quite different "meeting format" might be the next step. But whatever the answer, it will have to be sought actively by all concerned; passivity can only spell frustration and disastrous delay if not indeed total defeat for our time.

But having made these comments, what bearing do they have on the question at hand? What is the nature of the industrial involvement and of its responsibilities, direct and indirect, as far as the environmental health and safety aspects of its proposed commercial Plowshare activities are concerned? Acturally the answers depend on the way in which one projects his views of these operations into the future. The major Plowshare operations themselves might become a government monopolized business with industry simply hiring the government to do a job for them. If this were to be the case, however, a Plowshare industry of the magnitude one can readily foresee, should the envisioned activities prove to be commercially feasible, would put the government among the top elite of Fortune's Five Hundred. Unless the Commission's statutory mandate to use its powers to strengthen competitive private enterprise were revoked, I find it difficult to imagine such a development as even remotely probable. However, it is an admittedly possible outcome and, should it occur, industry's direct role in health and safety matters would be essentially nonexistent as far as the direct Plowshare phases of a project were concerned. Industry would still be directly concerned with the health and safety aspects of product processing and control, but only with respect to the problems involved in the commercial distribution of those products. It would also be vitally, if indirectly, concerned with the costs of the government's health and safety activities in its Plowshare operations, since these costs could well determine the total feasibility of any project. Important as these concerns may be, they require at most no more than modest direct industrial involvement.

If, however, the operating role of the government in Plowshare enterprises should eventually be limited strictly to the actual emplacement and detonation of the nuclear explosive (which operation, like its health and safety monitoring activities, must remain a statutory monopoly of the Commission for any foreseeable future) while preparation of the site in readiness for the emplacement and detonation becomes the responsibility of the concerned industry, then industry's responsibilities with respect to environmental health and safety assume a very different guise. They are no longer matters of indirect concern; they now lie at the very core of the considerations which determine the feasibility of a project in the first instance and, if feasibility seems assured, they play a dominant role in the operations that follow. Since I am personally convinced that a viable industry based on Plowshare technology can be established in the near future only if industry plays this sort of major management role, I will assume that this is the case in the discussion that follows. I must emphasize, therefore, that what I have to say has validity only to the extent that my assumption itself proves to be valid.

Even with this fullest possible management responsibility, however, there can still be extensive argument as to industry's precise function in health and safety activities. This is true both with respect to the establishment of the criteria of safety and the mechanisms for assuring that the criteria are enforced and with respect to the actual operations carried out under established regulations. Let us look first at industry's place, if any, in the development of a regulatory code.

It is easy to argue that, in this activity, industry has no responsibility and hence no role whatsoever. The Public Health Service holds under Congressional mandate the country-wide responsibility to ensure the protection of the national health. The Atomic Energy Commission is charged by Congressional statute with the ultimate responsibility of ensuring the public health and safety in those specific instances in which these might be affected by nuclear activities. None of these concerned organizations can abdicate these responsibilities either in whole or in part. Moreover, any governmental agency with regulatory responsibilities must emulate Caesar's wife. Not only must it make certain that other possible interests can in no way influence its regulatory judgments, it must assure that not even an appearance of such a possibility could exist. Thus, for industry even to suggest any direct initiative role in the development of the regulatory code under which its operations must be carried out would obviously be totally untenable. Clearly, those who would argue that industry should have no part, however remote, in this procedure have a persuasive case.

However, as I pointed out earlier, the trusteeship for insuring health and safety is inextricably enmeshed with the trusteeship for realizing Plowshare benefits, and industry bears a very direct responsibility with respect to the latter. Industry clearly faces a very real dilemma. If it takes the easy path and washes its hands of any part whatsoever in the development of the regulatory code, it avoids all possible hint of collusion - and a lot of hard work - but it may, by the same token, consign its incipient enterprise to an infant's grave. On the other hand, even to gesture toward the other extreme of playing a direct role in the development of the regulatory code would in my estimation not only be both inappropriate and inadvisable but would also constitute an act of self-immolation on a truly pyrotechnic political pyre.

But there is a defensible middle ground, and it is this that both industry and government must seek, difficult as that search may be. As to what constitutes safety and proper protection of health, the public itself, through the medium of its governmental structure, must say. No matter how knowledgeable industry may be in health and safety matters, its position is inescapably one that bears the appearance of bias if not of bias itself, and even the appearance of bias vitiates its opinions and judgments except insofar as they lend weight to the government findings by their concurrence. Where industry can properly contribute (and where its responsibility to the public under its Plowshare benefits trusteeship would dictate that it must) is in making it quite objectively clear just what are the associated costs to the economy of the proposed regulatory measures. It has been my experience that by and large in situations of this kind no one is more interested in this sort of demonstrably objective information than is the regulatory body itself. It has no desire to do its work with its overall vision blurred by a fog of uncertain or totally unavailable data from the economic areas of concern. It welcomes all the trustworthy information it can obtain on the true impact of its operations upon the activities it affects. Certainly the Atomic Energy Commission has a keen realization of its "secondary trusteeship" role, and I believe this is true of most other regulatory bodies. While I occasionally fume at what sometimes seem to be needlessly involved and ponderous regulatory procedures, I have never doubted the sincerity of the Commission's interest in attaining the full benefits which are latent within the fields of nuclear science and technology and which can be realized within its mandate to ensure the public health and safety. And I must confess that after numerous direct challenges by the Commission I have yet to suggest any very effective methods for simplifying its regulatory operations.

I am convinced that cooperation between Government and industry in establishing an effective regulatory operation is as much needed today as it was among the scientists and engineers in setting the safety standards twenty-seven years ago. I believe that the will to cooperate also exists provided a suitable framework for such cooperation could be established. While the mechanism of the official publication of a proposed regulation, of submitted comment, of official hearing, of rework, and of republication, etc., etc., etc., eventually produces a result of sorts, the cumbrousness of the method almost guarantees that the progeny so engendered will display appreciably less than genius rating. I will return to this later with a positive suggestion that I hope may prove to be of some value.

Let us now turn from the area of code generation to that of field operations which I have assumed will eventually be carried on largely by industry under such a code.

Here again, under present operating condictions, "participating industry" has essentially no role in the direct Plowshare phase of the project's field operations other than to take part in the planning and to pay a share of the bills; a share, I might add, that seems to be growing asymptotically toward "full cost" with perhaps improvident speed. Under present law a Plowshare project is of necessity a government enterprise in which industry may participate. Such an industry, however, must exercise its participation by serving in effect as a contractor to the Commission.

Let me break in here with an essential aside. To keep my comments on contracts in proper focus, I should warn you that after the War, General Nichols told me that it took the Manhattan District lawyers eighteen months to straighten out the contracts I had arranged during the first six months while the project was under OSRD auspices. I've learned a little about contracts since, but I'm still no legal expert. However, I've had a lot of experience in observing how these things actually work out, which may or may not be of the way they are supposed to do legally, and it is from this observational standpoint that I speak.

Now back to the argument. As things now stand, the Plowshare operator is the government, and the liabilities of its subcontractors, including its "participating industry" partners, are covered by the government. The government assumes full responsibility for all aspects of the necessary health and safety measures, and industry has in essence no responsibility except to obey explicit instructions. Here no code need to promulgated, for the regulator is also the only possible operator. Should an accident occur under present circumstances, the industrial contractors, including the industrial participants, would, I suspect, actually be numbered among the injured parties rather than among those liable and might thus escape both the direct financial liabilities and the indirect public relations liabilities which would otherwise be entailed. This being Las Vegas, I would bet a modest sum on the operating contractors escaping public damnation essentially unscathed, but I wouldn't risk a plugged nickel that the participating industries would receive that same public treatment. The former were just doing a job for the government and under the government's direct supervision, but the latter were the instigators of the affair who pushed the government into undertaking the task.

If there is to be any private industry based on Plowshare technology, we must clearly shift to the position I postulated at the start of my presentation, and then the above situation becomes markedly more aggravated, for now the entire operation, except for the actual emplacement of the nuclear explosive and its detonation, becomes the direct responsibility of private industry. From a purely practical viewpoint, I am convinced that when this happens, regardless of legal technicalities, industry must face the fact that, at least as far as public opinion is concerned, it will be presumed to carry the primary operating responsibilities and liabilities for all phases of the enterprise including that of environmental health and safety. For example, the government has fired so many underground shots without incident that should any accident happen, it would be essentially impossible to convince the public that the cause was other than negligent preparation of the site.

Now important as these considerations are at this point, I am not primarily worried about the financial liabilities involved. I am sure that adequate insurance will be available when required, and I have no doubt that as long as it is really needed, Price-Anderson coverage will continue to take care of any situation which might create financial obligations beyond the limits of the private insurance limits. But no Price-Anderson equivalent can be contrived that can "cover" the indirect, public relation liabilities which would be involved and which could prove to be fully as disastrous to industry as would the financial losses involved. It is this fact that convinces me that however legally sacred the Commission's specific mandate may be for insuring the public health and safety in all Plowshare activities, the brutal facts of the matter will prove to be that should the public health and safety suffer, it will be private industry principally, not the Commission, that will find its neck in the public's guillotine. It certainly behooves industry to make certain not only that any Plowshare enterprise it undertakes fully satisfies applicable governmental regulations but, even more, that it is indeed safe beyond any thinkable doubt according to its own analysis and experience.

Now obviously, the first step in undertaking any planned Plowshare enterprise must be the acquisition of formal government authorization to proceed. This serves a three-fold purpose from industry's point of view. In the first place it protects qualified industry from the serious, industry-wide damage that would ensue should some incompetent, foolhardy operator undertake a project which ended in disaster. In the second place, "passing one's exams" is a well understood facet of our society and is accepted as proof of qualification. This definitely carries over into authorization proceedings, and achieving authorization does become a valuable tool in gaining public acceptance for a project. Finally, and perhaps most importantly, the regulatory code constitutes an invaluable check list for industry's own safety analysis and its associated program of health and safety investigations. Also, the authorization proceedings themselves, when successfully negotiated, provide an important endorsement to the project management that their safety homework has been well done and that it is highly unlikely that there are any hidden holes remaining in its arguments.

Authorization constitutes a "necessary condition," but it is not necessarily a "sufficient condition" to assure total safety. As recent events in other technological areas have shown, government authorization provides no ironclad guarantee of safe operation. Consequently, as long as independent sources exist from which cogent question and competent answer can be obtained, industry will be wise to avail itself of their counsel and advice as well. No source of help should be ignored, every unwet heel should be explored no matter how minor its effect on the safety as a whole might seem to be. After all, one such heel accounted for Achilles' demise.

In the final analysis, however, industry must rely on its own internal competence in arriving at its final determination that its proposed operations are fully safe. There are many modes by which industry can achieve such competance ranging from major environmental health and safety divisions to compact, tightly knit but broadly competent evaluation groups. Whatever the mode chosen may be, however, its effectiveness is determined by three factors. The first and foremost is the intellectual quality and scholastic training of its members. The second is the breadth, depth, and appropriateness of their practical experience - the factor that gives them an instictive "feel of safety" as it were. The third factor is the degree of true communication that exists between themselves and their top management. Obviously the ideal situation is realized when one or more top executive officers could personally qualify for service within their own nuclear safety unit. But, however its internal nuclear safety competence is achieved, industry must place its ultimate decision-making reliance on that competence; and, until it has achieved such competence and has gained full confidence in it, it had better stay out of nuclear-based enterprises.

Continuing public concern and occasional outcry concerning all things nuclear constitute a major hazard in realizing the very real industrial benefits that are inherent in the nuclear field. This public concern has served one very useful purpose, however. Industry is no less a part of the public because it is organized as industry. In its days of nuclear naivete, it responds to nuclear affairs precisely as does the lay public; that is, with a deep-seated belief in the existence of unknown dangers and with serious apprehension as far as any direct involvement in nuclear affairs is concerned. The result has been that those industrial concerns that have tentatively ventured into the nuclear business have either had sufficient acumen to build unquestionable competence in nuclear safety and to do so on an urgent and comprehensive basis or they have gotten completely out of the business in a hurry. This has acted as an excellent societal bandpass filter. It has automatically eliminated from nuclear activities the vast majority of our society's normal fringe of foolhardy operators. Furthermore, it has insured that the sound participants do so on a level of competence that they might feel unnessary in some less sophisticated field even though the actual hazards were essentially comparable. The result has been that the nuclear industry is acutely safety conscious. It has built up exceptional internal competence in matters of nuclear safety, and in many instances it is already prepared to make its own operating decisions in those cases in which, in its opinion, its own "sufficiency" conditions establish tighter overall limitations on its operations than the statutory "necessary" conditions demand.

To summarize. The Government can advise on nuclear safety, it can and hopefully will establish a well-considered code of safety standards and regulations, and it can prevent the undertaking of any nuclear enterprise that it believes will imperil the public health and safety. It can authorize a project it judges to be safe and monitor it for adherence to the approved designs and operating procedures. But there its authority stops as far as the direct initiation of any given commercial enterprise is concerned. Only the responsible industry itself can give final approval to proceed with the actual field operations, and thereby it assumes the ultimate responsibility for all phases of the project's affairs including the liabilities involved in its environmental health and safety aspects. Indeed it would almost appear from recent occurrences that what is actually developing is the very strange situation in which an industrial decision to proceed under a government authorization becomes interpreted, at least by the public, as constituting a corporate endorsement of the scientific and technological validity of the government code and regulations under which the approval is granted. Regardless of how this may eventually turn out, it certainly emphasizes the importance of establishing an internal nuclear safety competence that is inferior to none within government or without.

Before turning to the final section of my discussion, I would like to interject a footnote on this matter of safety competence. One of the most serious hurdles that industry has faced and is still facing in the path of achieving fully effective nuclear safety judgments and consequent design and operating decisions in its Plowshare projects arises from the unavailability of essential pertinent data, which are presently held as classified information under AEC security rules. I have been assured by the Commissioners that this problem is recognized and that it is being placed in the hands of the Senior Responsible Reviewers. Once again the Senior Reviewers step into the communications breach which security classification always generates. The machinery which this voluntary Review Board provides sometimes seems frustratingly slow, but whatever the cost in slowness, it is more than paid for in the total objectivity which it achieves. Its performance in the reactor field was outstanding, and I have every reason to believe it will be equally so in the present instance.

Now where do we stand and what do we do next?

As far as the Plowshare program in general is concerned, it has successfully emerged from the laboratory as far as scientific feasibility is concerned and is ready for technological test and, hopefully, for eventual full economic exploitation. At the moment we are actively engaged in pilot studies in a number of important applications to determine whether technological feasibility can be demonstrated. When this has been accomplished the demonstration of economic feasibility and the attainment of public acceptance will constitute the two factors that still remain to be achieved before a full fledged if still infant industry becomes a reality. Industry alone is capable of determining economic feasibility. Indeed industrial "personality" being as distinct a characteristic of an industrial organization as it is, what may be economically feasible for one industrial entity may not be so for another and vice versa. As a result, the determination of economic feasibility of any given operation is only fully valid for the organization that carries out the pilot tests and from them makes its own determination of the feasibility of commercial operations. General paper studies of economic feasibility may furnish illuminating guide lines in determining whether a real test is worth the gamble or not and, if it seems worth while, in planning the test. In the ultimate result, however, generalized economic conclusions are likely to be of no more than strictly marginal usefulness in any specific case.

It is also upon industry that the primary responsibility for gaining public acceptance falls. With all other factors "go", it is this latter factor, the public's willingness not only to "tolerate" but actually to "buy" that determines whether there is to be a business or not.

As the Plowshare program now stands we find ourselves in the midst of an active joint government/industry program that, hopefully, will result in the demonstration of the technological feasibility of a number of promising applications and also provide valid preliminary data on their economic promise. Once this has been accomplished successfully, however, it is industry that must take the lead in undertaking the essential next steps if the applications visualized are to become a part of our private enterprise system, for it alone can decide whether the probable commercial benefits to be gained justify the investment required and the economic risks involved. Whether at this point a given industrial unit will find a given project to be economically feasible will depend in part, as noted above, on the peculiar capabilities of the interested organization itself and in part on the applicability to the specific test situation of the complex of technologies involved. With technological feasibility proven, there is no major factor in this complex which is of greater importance not only in determining the economic feasibility of the project but also in determining industry's ability to gain public acceptance than that concerned with the essential public health and safety activities required and the associated costs of these activities. Thus for the national Plowshare program to proceed with effectiveness and dispatch, it seems to me three immediate measures are particularly needed.

First, in order to achieve any really lasting progress, a tentative health and safety code covering design criteria, operational procedures, and end product specifications, should be set up in standard regulatory form to serve as a trial set of rules for immediate study and test use in the field operations involved in the up-coming experimental projects. The necessary information is available in a variety of forms and in a variety of places and is already being used by the AEC and its various contractors in insuring the environmental health and safety of all present nuclear detonations. What is needed immediately is not new data but an exercise in the formulation of the available data into an effective code of operating procedures and an analysis of its operating consequences. Such a tentative code would also serve as a concrete, "point-of-departure" statement in the development of the eventual regulatory code. The contemplated technological feasibility tests in the Plowshare program would provide an excellent means by which to evaluate its commercial applicability and to guide its evolution toward regulatory status. Here joint action is imperative if the resulting code is to meet the criteria outlined earlier in this paper. However, under these circumstances joint action is possible without prejudice because in this situation industry's contribution can be confined to the presentation of a running analysis of the strengths and weaknesses of the trial code in actual day-by-day practice as it sees it. In addition, the validity of its account can be weighed by concurrent government observation. The government agencies can then modify the rules or not, as they see fit, in the light of clearly observable operational experience. It seems to me that such an operation would promote the maximum of critical observation on the part of all concerned, would reduce any tendency on the part of anyone involved to resort to pressure tactics in order to substitute treasured belief for determinable fact, and would provide the best possible opportunity to arrive at a regulatory code that would not only insure the environmental health and safety of the public but would also protect the public interest in the benefits that successful exploitation of the Plowshare technology seems capable of providing.

Next, if the foregoing exercise is to be meaningful within the adjunct economic framework, the research and development aspects of these upcoming tests with respect to health and safety investigations, important as they most definitely are, must nonetheless be scrupulously separated, at least costwise, from the necessary health and safety operational activities as specified in the provisional code. This I realize can be operationally difficult. Moreover, no one knows better than I how cogent the considerations of budgetary expedience are that argue for burying these costs as unscrambleable shards in the total heap of operational budgetary artifacts. In this case, nevertheless, no matter how hard it may be to unscramble the activities and however tough the resulting budgetary sledding may be, such budgetary integration simply cannot be allowed either within the governmental agencies or within the participating industries. Honest, "unloaded" operating costs are an absolute must if the tests themselves are to be meaningful.

Finally, throughout each such exercise it must be recognized by all concerned that time is one of the most significant factors in determining the success or failure of any industrial endeavor. The present case is no exception. In the university or the research laboratory, we can usually downgrade the importance of time and do so safely. This is neither a matter of sloth nor neglect of duty. It is just true that in the laboratory cautious conservatism and the desire for perfection outweigh the need for speed. But this is not true of an industrial activity. The time factor must be kept continually in mind, for delay can spell defeat for a commercial activity just as surely as can direct technological failure. Whenever a contemplated course of action will impose delay, it is vitally important that the anticipated advantages be weighed meticulously against the possible detriments lest the hope of small gains inadvertently lead to the achievement of total ruin. Here again the truly judicial sort of appraisal required can be realized only to the extent that open communication and joint evaluation procedures can be established.

In conclusion, I would simply like to reiterate what I at least implied earlier. As far as the nation is concerned, all of us connected one way or another with the Plowshare business are in the same boat. As is true with all industrial activities dealing with hazardous materials, the operations with which we are concerned do bear potentials for serious damage to the public health and safety if carried out blindly and without due regard for safe practice. Everyone involved will reap the whirlwind if any of us sows the wind with some act of thoughtlessness or negligence. We are all convinced that accidents are made, they do not "just happen," and that proper safety practice scrupulously followed by all not only can but will insure that they will not occur. Each member of the team has his own role to play in this achievement, and everyone involved is mutually dependent on the others to attain the necessary total safety surveillance. It should be noted also that the cornerstone of safety practice is quality of performance not quantity of service. True safety can be smothered within the overlap arising from an unbridled proliferation of safety measures. I believe that we would all agree that a taut ship manned with a crew notable for its high personal abilities and its skilled teamwork rather than its astounding numbers, and equipped with every essential tool of the nuclear safety trade can maintain a total blockade on nuclear accidents and do so indefinitely. It is this that constitutes our mutual goal.

In addition, if we plot our course in this way, we will also have taken the necessary steps to assure that our second objective, the realization of the benefits inherent in Plowshare technology, will be attained if they prove to be technologically feasible and economically attainable. If despite our best efforts commercial utilization eludes us at the present, we will at least have the satisfaction of knowing that our enterprise failed honestly at the hand of a sympathetic and fully educated reason and that it was not the inadvertent victim of a well-meaning but misguided emotion.

ROLE OF THE ATOMIC ENERGY COMMISSION

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ABSTRACT

Public health aspects of nuclear explosions fall into two categories: (1) operational safety during the conduct of the explosion; and (2) the regulation of by-product material resulting from the explosion. By statute, the AEC has the responsibility for both assuring operational safety and regulating by-product material.

Current AEC safety and regulatory practices are described; future problems or needs discussed; and relationship to federal, state and local governments outlined.

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It is with considerable trepidation that anyone presumes to speak on the future role of a government agency in a hypothetical future. As I am sure you are well aware, there are many factors that bear on this subject, not the least of which are the prerogatives of the U. S. Congress and the President in matters of executive branch organization and reorganization. Thus, anyone has to speak on this subject with certain qualifications.

I take some cheer, though, in the fact that one of the things carved in stone in Washington is: "What is past is prologue." With this in mind, I believe we can look at the present responsibility and authority of the Atomic Energy Commission (AEC) and their source in the Atomic Energy Act and draw some conclusions about the probable role of the AEC in the event that Plowshare technology finds large-scale use.

For purposes of simplification, I would like it understood that I am speaking about the role of the AEC solely in connection with the use of Plowshare technology in the U. S. However, in light of our obligations under Article V of the Non-Proliferation Treaty, it is clear that the AEC will also have a role in furnishing nuclear explosion services in other countries.

The basic mission of the AEC is found in the Atomic Energy Act of 1954, as amended, where the AEC is charged with promoting, "the development and utilization of atomic energy for peaceful purposes to the maximum extent consistent with the common defense and security and with the health and safety of the public." The Act further charges the AEC with establishing "by rule, regulation, or order, such standards and instructions to govern the possession and use of special nuclear material, source material and by-product material as the Commission may deem necessary or desirable to promote the common defense and security or to protect health or to minimize danger to life or property."

It is also worth noting that the Atomic Energy Act stipulates that subject to the paramount objective of assuring the common defense and security, atomic energy should be directed "toward improving the public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace." Strengthening free competition in private enterprise has provided a keynote that the AEC has faithfully followed in developing all the peaceful uses for atomic energy, including Plowshare. Basically, this provision has been taken to mean that in developing any particular use for atomic energy that the AEC role should be to continue its development only until it can demonstrate the practicality of a particular use. Once that has been done, the AEC has tried to confine its role to the minimum necessary to meet its health and safety or other responsibilities and to leave exploitation of the developed technology to industry or other entities which have such roles in our society.

To implement the Act, a Commission is established, composed of five Commissioners appointed by the President, one of whom the President designates as Chairman. The Commission is, of course, the policy making body of the AEC. The agency the Commission heads is then divided basically into two distinct and deliberately separate areas, one under a General Manager and one under a Director of Regulation. For purposes of understanding AEC roles, this distinction is very important.

Under the General Manager are the operational and promotional functions of the agency. These functions include research and development programs, such as Plowshare, in which technology is developed to be made available to others.

The Director of Regulation is responsible to the Commission for the licensing and regulatory responsibilities laid down in the Atomic Energy Act. These include the licensing of reactors, special nuclear, source, and by-product materials; the development of proposed standards for radiation protection as well as corresponding rules and regulations; the inspection of licensees for compliance; and the development and administration of programs with the States in the field of licensing and regulation.

Both the operational and regulatory sides of the AEC can be expected to have a continuing role in Plowshare in the event of its large-scale use.

Up to now, the operational side of the AEC has been concerned with developing the technology for peaceful nuclear explosions, including carrying out the necessary experiments to determine the feasibility of various applications, such as excavation, gas stimulation, gas storage, copper leaching, and oil shale recovery. In these experiments, such as Gasbuggy, the AEC has been responsible for insuring the health and safety of the public.

On the regulatory side of the AEC, in anticipation of the eventual commercial use of this technology, the staff has been looking at the question of regulations for distribution of products such as natural gas that will be produced with the aid of nuclear explosions.

Before proceeding further to talk about a "future role," however, I think it would be desirable to say a word about "present status" of the Plowshare technology. As we see it, the program has entered a transition period where some of the applications are approaching a practical or "commercial" level. I stress the words, "entered," "some" and "approaching." None of the applications being developed have as yet reached that stage; nor will they all reach it at the same time. Some applications are more advanced than others and will therefore be ready for commercial use sooner.

Since Plowshare began some twelve years ago, we have always foreseen and have been working toward a situation in which the AEC will be providing a "commercial" nuclear explosion service for "developed" activities. We have also recognized that because of the uneven rate of development of the various applications, we would continue to have an experimental program.

To provide for this future, Mr. Hosmer has introduced legislation in the U. S. Congress, supported by other members of the Joint Committee on Atomic Energy, which would provide the AEC authority to carry out detonations for other than strictly AEC research and development purposes. This legislation also charges the AEC with making provisions in its contracts, for the service, relating to the protection of health and minimization of danger to life or property.

Regarding this future "commercial" explosion service, I believe it is clear as far as we can see that the legal requirement for the government to maintain custody and control of the nuclear explosive will continue. Therefore, the "commercial" nuclear explosion service will consist of the design and fabrication of the nuclear explosive, its transportation to the emplacement site, supervision of its emplacement, and its arming and firing. The service is also seen as including appropriate technical reviews of the proposed detonation, such as those necessary to fulfill AEC safety responsibilities connected with the detonation.

In other applications, where we would still be conducting research and development experiments, I do not foresee the situation being much different than it currently is.

In the foregoing discussion I hope I have conveyed my feeling that, because the program has been evolving gradually in the commercial direction, we do not foresee a dramatic, clear-cut transformation of Plowshare. We expect a continuing evolution, not a revolution. this is true not only for the technology, but also for the standardized procedures needed for commercial operations in such areas as security, indemnification, site disposal and health and safety. I believe various "roles" will evolve just as the technology and procedures evolve.

Having set the stage for the future, I would like to turn now to a more detailed discussion of how the future role of the AEC might evolve for providing a "commercial" nuclear explosion service, with particular reference to the health and safety field.

Essentially, I believe the health and safety role of the AEC can be expected to remain the same as it is now. From an operational standpoint, whether the detonation is for experimental purposes or for commercial applications, the AEC will undoubtedly be responsible for a final evaluation to insure that steps are taken or available to avoid any effects of the nuclear explosions materializing into a hazard to life or property.

A very significant step toward handling the safety function in a commercial situation has already been taken in our current procedures for working with industry in joint experiments. Starting with the Rulison experiment, the AEC has been expecting industry to collect the required data and to develop a comprehensive safety plan. In these early joint experiments with industry and until appropriate criteria are developed and published, the AEC is working closely with industry to provide guidance in the development of these safety plans.

Accordingly, using the rationale that our current procedures provide some useful clue to our future activities, I'd like to sketch briefly how we handle the safety function in joint experiments with industry today.

First, I want to emphasize that safety, even in these joint experiments where industry is assuming a greater role, is not simply an added factor to be considered after an experiment is designed. It is not, so to speak, an appendage to the main body of an experiment. Rather, safety is an integral part of an experiment, from its inception, through the planning, the selection of the proper explosive, its fielding and execution. This may seem to be an obvious point, but we so often hear safety spoken of as something apart from an experiment--an afterthought to its actual design--that I believe it is essential to emphasize that safety has to be built into any future Plowshare project from the start, just as it is today in our experiments.

Currently, the Division of Peaceful Nuclear Explosives (DPNE) has assigned responsibility to the Manager of the Nevada Operations Office (NVOO) to work with industry in the planning and execution of these Plowshare nuclear experiments in conjunction with the scientific laboratories. This procedure insures that all the experienced organizations and technical and operational resources that have already safely detonated hundreds of nuclear explosions are available in the planning and execution of joint industrial experiments. This, of course, includes our hosts for this important symposium--the U. S. Public Health Service.

As the detailed safety plan is developed setting forth the monitoring and safety procedures, it is reviewed by Nevada's Effects Evaluation Division and other participating agencies such as the U. S. Public Health Service. Every effect of the explosion is analyzed in terms of its potential for creating a hazard. Specific problems not previously encountered can be referred to consultants from universities, industry, or other government agencies having expertise in the problem area.

In addition, plans for the explosion are reviewed by the Test Evaluation Panel. This panel's primary responsibility is to ensure that every feasible measure is taken to prevent inadvertent releases of radioactivity. Extensive reviews are made by the panel of the construction of the emplacement hole, the geology of the site, the location of other holes in the vicinity and the stemming plan for the emplacement hole.

After all the detailed planning, reviewing, cross checking and double checking is completed, and the Manager of NVOO is satisfied that the explosion can be conducted safely and that precautions have been worked out to cope with any eventuality, no matter how remote, execution authority is requested through DPNE from the AEC. Final responsibility for assuring the safety of any nuclear detonation resides, of course, with the AEC and the AEC must give specific authorization for each detonation.

The AEC's safety responsibility does not end with authorization of the detonation. Safety reviews continue up to the actual detonation. At any time, up to the final second, an AEC Test Manager can stop the test if any indication arises that it might create unacceptable hazards.

That briefly is the safety role the AEC plays in joint experiments with industry. Let me add that we recognize the need for and are developing some generalized guidance and criteria for radiation, ground motion, and air-blast so that industry can know with some certainty what will be required of it in connection with Plowshare projects. Until formal criteria are available, however, we will continue to work closely with individual companies in providing them guidance on these matters.

I might add at this point that the AEC also has a general responsibility for seeing that the data on which our reviews and evaluations are based are continually reviewed and refined. In order to fulfill this responsibility, the AEC supports an active research and development effort in subjects related to safety. A specific example of this general effort in the case of Nevada is its Panel of Safety Consultants, composed of recognized authorities in such fields as hydrology, geology, structural engineering, geophysics and soil and rock mechanics. This Panel reviews the safety program associated with nuclear testing and recommends what directions new research should take.

In order to make this as comprehensive a commentary as possible, I'd like now to touch briefly on the AEC's regulatory role in the event of large-scale use of Plowshare technology.

The Atomic Energy Act of 1954, as amended, provides that the AEC is responsible for governing "the possession and use of special nuclear material, source material and by-product material...to protect health or to minimize danger to life or property." By-product material is defined as "radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material." As the radioactivity intermixed in products recovered by using Plowshare technology would be "by-product" material under this definition, it will be subject to regulation by the AEC.

The AEC regulates by-product material by granting licenses or exemptions from licenses where appropriate. That is, no person may manufacture, produce, transfer, acquire, own, process, import or export by-product material unless he has been granted a license or an exemption by the AEC.

The regulatory process as it applies to the distribution of products containing by-product material was discussed earlier in an excellent paper by Dr. Western and Mr. Rogers--for those of you who didn't hear it I urge you to obtain a copy and read it. Since they covered the topic so thoroughly, I don't intend to go into detail here.

Briefly, as Dr. Western and Mr. Rogers indicated, the distribution of Plowshare-recovered products on a commercial scale involves different factors than those considered by the AEC in its present regulations. Accordingly, regulations, specifically addressed to Plowshare applications, will have to be developed. This is not to say that our present regulations and experience will not provide some useful guidance. Here again, as we found in our discussion of operational safety, and as Dr. Western and Mr. Rogers also pointed out, in controlling the public distribution of other products containing radioactive material, there are many factors that have received extensive consideration by the AEC that are also pertinent to the development of regulations for the control of distribution of Plowshare products.

For example, the AEC has exempted from license certain consumer products, such as luminous wristwatch dials or compass needles, containing by-product material. In those cases, it is simply not practical to regulate users of the product. Instead, the AEC has developed criteria for determining whether the product sufficiently limits its potential for exposure to members of the public to justify exemption of its possession and use from regulatory control. In these cases, regulatory controls are applied to the producers, importers or distributors of the product to assure that the exempt product meets the specified requirements. The consumer product exemption situation is similar to the situation of Plowshare recovered products where again it is not feasible to license directly all the users of products.

Dr. Western and Mr. Rogers pointed out some of the considerations that should be taken into account in developing suitable criteria for distribution of Plowshare products. These include:

1. The contribution of the Plowshare-produced product to the national welfare.
2. The feasibility of limiting radioactive contamination of the product, as released by a licensed producer or processor, to acceptable levels.
3. Possible and probable exposures to individuals and population groups as a result of exemption of the product from regulatory control under specified conditions.

In addition to these general considerations, as in other areas of regulation of radiation, the development of criteria and regulations for distribution of Plowshare-recovered products will be guided by the recommendations of the International Commission on Radiological Protection, the National Council for Radiation Protection and Measurements, and the Federal Radiation Council.

There are two other points that Dr. Western and Mr. Rogers brought out that bear repeating in this brief summary of their remarks. First, our regulatory staff does not believe it will be appropriate or reasonable to establish a single limit applicable to all situations. Second, it is likely that the regulatory controls that will initially be imposed on distribution of Plowshare-recovered products will differ from those at a later time when the technology has been more fully developed, when pathways of exposure and the affected population groups are better identified, and when the accuracy of theoretical exposure models have been confirmed by field assessment.

In conclusion, I think it can safely be said that the role of the AEC in the event of large-scale use of Plowshare technology is expected to evolve gradually with time and the changing state and needs of the technology. We believe this is both administratively wise and technically sound. We hope you agree.

ROLE OF THE PUBLIC HEALTH SERVICE

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ABSTRACT

The Public Health Service must assume the role of the overall Public Health Coordinator, seeking to afford the highest level of health protection both to the nearby population as well as to the more distant groups. Data will be given relative to the limited experience the PHS has had in the removal of populations from areas of suspected hazards. Problems inherent in the evacuation of civilians of all ages will be discussed.

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The privilege one feels in being able to participate in an event of this kind always is heightened when he also is a member of the sponsoring organization. I trust my estimation of the value of this symposium is not biased by my dual capacity. I am convinced that our efforts here have been greatly needed.

In the first place, we have needed this symposium to help us lay the basis for the health and safety guidelines we must have for the large-scale peaceful application of nuclear explosives. This event is providing us, furthermore, with a much needed opportunity to examine problems which may arise as the promise of this new technology unfolds.

I am going to talk about the role of the Public Health Service in the large-scale use of nuclear explosives for peaceful purposes. It will become clear, as I proceed, that woven through this talk is a theme, which, however often you may have heard it at this symposium or elsewhere, deserves to be repeated. It is that the public health role in assuring the protection of the health and safety of the public is absolutely critical to the future of projects for the peaceful uses of nuclear explosives.

My symposium presentation will be made in two parts. The first part, which is applicable to the detonation phase of Plowshare projects, will be devoted to a case-history narration of two events illustrating public health protection on a large scale.

The second of the two principal parts of this presentation is a discussion of the role that the Public Health Service should have in evaluating each Plowshare project from a public health viewpoint both for the operational and post-operational phases.

We will begin our narration by discussing the case histories of two events which represent a rich source for guidelines to Plowsahre safety. The events were quite different in many respects. In fact, in one of them, chlorine gas, rather than radiation, was the agent of potential health impairment or, possibly, death. In one very important respect, however, the events were quite similar and it was because of this similarity that they were chosen for this talk. In both events neither serious injury nor death was caused by hazardous agents against which protective action was taken; yet, in each case, measures were adopted which represented something close to the ultimate in precautions for safety, including the evacuation of hundreds of people.

Each action program, in other words, rather completely reflected the Public Health Service viewpoint of what one should do when confronted with a potential for the impairment of human life on a large scale. One should prepare for the worst. One should cover, or try to cover, every eventuality. One should recognize that public health protection can be exercised only when adequate plans have been developed and tested. The Salmon Event of Project Dribble was the detonation of a five-kiloton nuclear device 2,720 feet underground in a formation known as the Tatum Salt Dome near Hattiesburg, Mississippi, in the fall of 1964. The PHS, under a Memorandum of Understanding with AEC, had certain responsibilities for the civilian population who lived adjacent to the active test site. These responsibilities were not different from those we exercise here at Nevada.

I shall not detail all the preparations here. These included a great amount of environmental surveillance, the collection and analysis of meteorological data, studies of milk from the area's dairy industry, the establishment of communications networks for the rapid dissemination of information to operating personnel and the public.

Most of our work with people was in conjunction with the evacuation of 451 persons, representing 105 families, from portions of the off-site area selected on the basis of fallout predictions for the anticipated weather conditions and ground motion. We called on every family which was to be evacuated. We knew the first and last names and, sometimes, the nicknames of each member of every evacuee family. We knew who was sick and what ailed them. We made almost daily checks on the condition of the ill and the enfeebled elderly, knowing how this may change hourly. Incidentally, the change may come in forms one may not always anticipate, as when a married daughter in one family decided to come home to have her baby just before the shot.

We knew how and where we were going to move each sick person, having made arrangements with his physician and, when necessary, with hospitals. It was decided to have the sick moved not only by personnel trained in this work but by local people who would have moved the ill in this community in any emergency. This proved a wise decision, since the appearance of familiar faces on moving day had a calming effect on patients. It is necessary to emphasize, I think, that planning for the evacuation and care of people must take into consideration the individual needs of each evacuee.

Having decided to move sick people by ambulance in advance of a shot, we soon had to make another decision, which was whether the sick were physically able to make the trip back home. Before-and-after conditions are not always the same. Furthermore, persons moved into hospitals are no longer home patients, but hospital cases. They are subject to hospital feeding, care, and routine and may be released only with the consent of their physicians or if they sign themselves out. One of our evacuees remained in the hospital for ten days.

All evacuation expenses were borne by the project, including, of course, payments for ambulance services, hospitalization, and other medical care. All evacuees were paid a specific sum per adult and a specific sum per child for each day they were away from their homes. Payments were made by check, and facilities were at hand for immediately converting checks into cash.

Surveys made of people in advance of their evacuation and in connection with the security of their properties provided excellent opportunities for the establishment of confidence, understanding, and personal relationships which provided a solid basis for our public relations program - and very often, in fact, were the major content of that program. During these discussions, people were individually informed concerning all project activities, and sometimes were informed by us before they had a chance to read about it in their newspapers. The value of these relationships cannot be overemphasized.

It cannot be overemphasized that the very best relationships must be established between State and local police, other public safety personnel, and the local medical community. People tend to have confidence, particularly in a relatively small community, in what they are told by the police chief or sheriff's deputy or the president of the local medical society. No outsider's communications skill can match a few reassuring words from a local authority who people know and often may regard as friend. The most significant non-technical finding produced by this public relations program was the knowledge that a comprehensive off-site radiological safety program can be conducted in a populated area provided the people's confidence in the operation is established and maintained.

Operation Safeguard provides my second case history of a large-scale action program for safety and public health protection. Six hundred and one persons, all of them ill and aged, were evacuated in this instance. The locale was Baton Rouge, Louisiana. The agent for death or health impairment was chlorine gas. The time of peril for tens of thousands of people ran for 64 days.

It started on September 10, 1965, when Hurricane Betsy, rampaging through the Louisiana capital, tore a barge from its moorings and swept it ten miles down the turbulent Mississippi River before it sank in 60 feet of water with a cargo of four 150-ton tanks of chlorine under pressure and in liquid form. The end came on November 12 when the barge, its cargo intact, was plucked from the Mississippi mud by a giant crane.

One hesitates trying to name all the public and private agencies involved during the 64 days spent protecting people and in the salvage operations. They included the Army, Navy, the State Departments of Welfare and Hospitals, and the Board of Health, the State Police, the Louisiana Civil Defense Agency, area hospitals, the Red Cross, medical societies, and the U. S. Public Health Service. Early in October 1965, the Departments of Welfare and Hospitals of the State conducted a three-day survey of the ill and the aged within an area extending five miles on all sides of the sunken barge. Between 500 and 700 patients were estimated to be there.

In late October arrangements were made with the Fourth Army to send two hospital trains with seven litter cars and one kitchen car each and five litter buses for evacuation. Twenty ambulances and five buses were supplied by the Department of Hospitals.

Around this period and for some time afterward, the fear grew that a small leak might develop in a valve in one or more of the tanks. Had this occurred, the resultant hydrochloric acid might have eaten away the remainder of the valve and 150 tons or more of potentially lethal chlorine would have been released, much of it blown as gas to the surface of the river. It was against this eventuality that Public Health Service personnel analyzed air and water samples approximately every 30 minutes around the clock.

In addition to planning for evacuation of the sick and the aged, preparations were made for a mass exodus of people. Evacuation routes were selected and maps were reproduced by newspapers and television stations. Shelters were set up at strategic locations and 40,000 cots and blankets were furnished from Public Health Service medical stocks.

It is unlikely that any potential, or even actual, disaster ever resulted in a communications system more complete than the one in use at Baton Rouge in the fall of 1965. To describe it would take more time than we can allow. Its existence was a recognition of the paramount importance of communications to efficient operations management, as well as to keeping the public quickly and accurately informed of developments at all times.

The first evacuation train left Baton Rouge on November 10; evacuation was completed 22 hours later. Fear vanished the day the barge was raised with its four chlorine tanks intact. With the exception of two elderly heart patients who died en route and one too sick to be moved, all evacuees were back home by November 14. As for others in the area, schools and businesses were closed in Baton Rouge on barge-raising day, November 12, and people generally remained in their homes, as urged by authorities, or left the city for the country upwind from the site.

One illustration, among many, of the degree of preparation at Baton Rouge for a disaster which never occurred is provided by the first-aid station custom-built from an obsolete X-ray bus by a Public Health Service officer and Army soldiers. It was equipped especially to care for chlorine gas and burn cases. A filtering device was available to clear chlorine gas out of the station and replace it with pure air. Four pressure inhalators were available for the administration of drugs against lung congestion which is the worst effect of the gas. Drugs and ointment were on hand for the treatment of chlorine burns of the skin and eyes. But there were no chlorine emergencies. There were colds and minor cuts and bruises, fractures of fingers or toes. The most serious injury was a broken leg.

Although the examples provided by the Baton Rouge incident and the Mississippi nuclear Project Dribble are different in many respects, nevertheless they reflect an off-site condition of the kind we can assume might develop as Plowshare projects become more widespread. In each case, large numbers of people were under conditions of possible exposure to agents potentially hazardous to health.

As long as these events are experimental, we are going to have to program safety and health protection for Plowsahre as though we expected the most improbable event to occur. The public must know that safety preparations for possible events have been made or the public will not condone, much less support, efforts to perfect Plowshare technology.

The second part of my presentation concerns the role of the Public Health Service in evaluating each Plowshare project from a public health viewpoint. It is recognized that the conduct of a Plowshare nuclear detonation is an AEC responsibility by statute. The AEC controls the execution of all phases of the operation involving the nuclear device, including site preparation, emplacement, detonation, disposition of radioactive substances, and health and safety. In my judgment, it is the responsibility of the Bureau of Radiological Health, i.e., the PHS, to make a public health evaluation of each Plowshare project. This evaluation should relate to the operational aspects of the actual event, and the production, handling, storage, distribution, and use of the resulting products. The review and evaluation should be initiated as soon as sufficient preliminary information is received and developed. As part of the evaluation, the known as well as the unknown information relating to public health would be delineated. The technical evaluation will encompass the usual operational considerations for the immediate off-site area at the time of detonation, as well as considerations of the long-term and long-distance implications such as the distribution of consumer products resulting from certain nuclear explosive applications.

It is the mutual responsibility of industry of several States and Federal agencies to insure that any resulting radiation exposure from Plowshare projects is kept as low as practicable and within acceptable limits. At this time it is most appropriate to discuss the applicable guidance for radiation exposure. In my judgment, this symposium contributes to a free exchange of ideas and information that will be helpful as we attempt to resolve problems in this area. Because of the uncertainties in the distribution of radioactivity in the final consumer product, it is extremely important that both Federal and State Health agencies be knowledgeable as to the sources of radioactivity that may result in an exposure to the population. In order to carry out their respective responsibilities, public health officials should be kept currently and fully informed of proposed projects and resulting releases of radioactivity.

The basic guidance for public health consideration of radiation exposure is that promulgated by the Federal Radiation Council (FRC) and directed by the President to be used by Federal agencies. The FRC was established in 1959 by Public Law 86-373 to provide a Federal policy on human radiation exposure. A major function of the Council is to " . . . advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in establishment and execution of programs of cooperation with States . . . ."

The Radiation Protection Guide (RPG), which is defined by the FRC as the radiation dose which should not be exceeded without careful consideration of the reasons for doing so for the general population, is 0.5 rem/yr whole body dose for an individual. This guide is applicable to normal peacetime operations and is not intended to apply to radiation exposure resulting from natural background or the purposeful exposure of patients by practitioners of the healing arts. There can, of course, be quite different numerical values for the RPG, depending upon the circumstances.

As an operational technique, where the individual whole body doses are not known, a suitable sample of the exposed population should be developed whose protection guide for annual whole body dose will not exceed 0.17 rem per capita per year.

The Radioactivity Concentration Guide (RCG) is defined as the concentration of radioactivity in the environment which is determined to result in whole body or organ doses equal to the RPG. The use of RCG's is an operational technique which provides a means to evaluate potential human exposure based on measurement of environmental concentrations of radioactivity. An RCG must be based on an RPG and is applicable only for the circumstances under which the use of the corresponding RPG is appropriate.

Effective radiation control measures for any health hazard will require the establishment of radiological safety procedures and guidance for health agencies to reduce any potential hazard to an individual or the public to as low a degree as practical. Establishment of these control procedures requires value judgments in which the potential risks of the hazard are weighed against the benefits to be derived. Because of this need, the health agency must have sufficient technical information related to the problem to derive workable control procedures. This is needed along with scientific knowledge concerning the biological effect of the ionizing radiation to adequately evaluate the magnitude of the hazard under the given condition. All agencies involved in the peaceful nuclear explosives program must understand that this guidance is needed to assure protection of the individual and the public and to permit anticipated benefit to the public.

Other groups concerned with population risk should be consulted to assist in the review of all factors which may affect the impact of the guidance on the consumer.

Concentration guides provided by the NCRP and ICRP, supplemented by guidance provided by the FRC, are applicable to total exposure of the public to radiation from all sources (except medical uses and natural background), and do not provide specific guidance for exposures to individual sources. Appropriate guides for a particular application of nuclear energy should be based on the following considerations: (1) Activities resulting in man-made exposure should be authorized only under conditions for which it is determined that the benefits outweigh the risk; (2) Within these conditions, radiation exposures should be limited to such levels that the reduction in risk associated with any further reduction would not justify the total effort.

It is my understanding that radiation limits for Plowshare Projects will be established by the AEC's regulatory group under the procedures set forth in the Code of Federal Regulations. However, the limits for commercial products associated with Plowshare applications may not be developed until the projects change from an experimental to an industrial application phase. Further, it is recognized that the FRC has applied general guidance for these applications. For instance, the present AEC position regarding regulatory limits for natural gas applications limits is as follows:

> " "The AEC has not developed regulatory limits which are directly applicable to the gas storage application and it is expected that the results of the experiment would be used as a partial basis for developing such limits. These limits may be some small fraction of the FRC guides or of the recommendations of the ICRP and NCRP. After satisfying the experimental requirements, any commercial use of storage gas from the chimney containing radioactivity would be subject to appropriate regulatory approval. Such approval would be granted only after a determination has been made that use of the gas would not result in a significant increase in the radiation exposure normally received by the general public."

It seems clear to me also that there can be no planning compatible with a given use of explosives without close cooperation between the developers of the explosive device and public health authorities. No device ought to be brought to a mature state of development by nuclear specialists working independently. If the public health is to be adequately protected, input from public health specialists must be accepted at an early stage.

Looking back over the Plowshare experience, I believe the capability probably is available to insure that nuclear explosives can be used for peaceful purposes, on a large scale, either without human and environmental exposure or with exposure at acceptable levels. As yet this capability has not been demonstrated. Nor do I think that the American public fully believes the capability exists. I trust, however, that the time may be nearing when we can agree, from the public health standpoint, that Plowshare is ready to move forward as a tool for progress. This, ladies and gentlemen, is the goal we seek.

ROLE OF A STATE HEALTH DEPARTMENT IN AN UNDERGROUND NUCLEAR EXPERIMENT

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ABSTRACT

When Project Ketch was first announced to Pennsylvania state officials, the Department of Health, under its legal responsibility to protect the health of the citizens of the state, was quick to realize that a thorough, independent review of the proposal was indeed necessary. Although the project was terminated by the sponsoring company before on-site preliminary evaluation work was begun, it is believed that the Department's approach was sound and practical. This study and the planned joint effort of the state and the Bureau of Radiological Health will be discussed in detail.

* * * * * * * * * * * * * * * * * *

We, in Pennsylvania State Government, were involved for approximately two years in a proposed Plowshare experiment entitled Ketch. Our experiences, our reactions, and the reaction of the public sector is important to discuss, especially if future Plowshare programs are to succeed in the Northeast. This is that story.

Project Ketch is a joint proposal by the Columbia Gas Corporation and the Atomic Energy Commission to create an underground gas storage reservoir with nuclear explosives. Since gas storage is essential in providing adequate service at reasonable cost during times of peak demand, it would seem appropriate to provide such storage capacity in areas removed from the gas fields where demand was increasing beyond the present capacity of the gas delivery system.

The experiment should naturally be carried out in geological formations which would provide adequate safety and still fulfill the requirements for adequate gas storage. Pennsylvania seemed to be an ideal location for such an experiment because of its location in the rapidly growing Northeast and its tight geological structure.

Early in 1966, we were officially informed that the Columbia Gas System Service Corporation and the Atomic Energy Commission were seriously considering Pennsylvania as a site for the Ketch experiment. My first reaction, and I think the reaction of many state officials, was one of disbelief. A nuclear device being exploded in our backyard? Unbelievable! Nevada, with its sparse population and open spaces, was a far cry from the populated Northeast.

However, after we recovered from the initial shock and began to consider the situation in more detail, we all realized that it was not our responsibility to react from emotion, but only from cold, hard, fact and reason.

What were our responsibilities? Only one--to evaluate the experiment from the standpoint of public health and safety and approve or disapprove of the proposal. But immediately, many other obvious questions arose. What were the facts? What kind of information did we need to evaluate the project? Where would we get the expertise to evaluate information we did receive? And, although it was never really raised in public, one question continued to gnaw in the backs of our minds . . . "Could the Atomic Energy Commission be relied upon to conduct the experiment in the safest possible manner, especially when they were also attempting to promote the use of nuclear explosions by showing that such projects could be conducted at reasonable costs?" Did the AEC have a review mechanism similar to that which has worked so effectively in the reactor licensing program? What was this mechanism?

Very little information was immediately available on the safety aspects of underground nuclear explosives. The literature was almost devoid of good references. How much of the information was classified and could we gain access to it?

Meetings were held with representatives of the various state agencies which would have to be involved. The list is longer than one would imagine. Besides the Department of Health, it included:

1. The Department of Forests and Waters, which was responsible for leasing the use of state lands;
2. The Department of Mines and Mineral Industries, which has responsibilities for gas and oil well drillings;

3. The State Geological Survey, which had interest in the information to be obtained during the evaluation phase of the project;

4. The State Fish and Game Commissions were involved, because of possible effects on the wildlife;

5. The Public Utility Commission, which regulates the local gas industry; and

6. The Department of Commerce, because of its role in the developmental aspects of the atomic energy industry.

In January of 1966, former Governor Scranton signed into law the Atomic Energy Development and Radiation Control Act. This law provided, and I think rightly, that the developmental aspects of atomic energy be placed in the existing Pennsylvania Department of Commerce and that regulatory activities be placed in the Department of Health. It also provided for an Advisory Committee to assist both Departments in the administration of their respective endeavors. These nine committee members were appointed by the Governor, confirmed by the Senate, and represented the varied interests in and aspects of atomic energy, and included individuals from industry, labor, education, medicine, radiology, health physics, and related sciences.

The Committee is directed to make recommendations to the Department of Health, review rules and regulations, and furnish such technical advice as may be required on matters relating to the control of radiation.

The Ketch proposal was discussed in detail, and as more and more information became available, the Governor and the Departments requested a complete evaluation of the project including appropriate recommendations. A special "Ketch" subcommittee was established by the Advisory Committee to provide additional scientific expertise in areas which were not covered by individuals on the main committee. It was chaired by an expert in nuclear engineering and presently the Dean of Engineering at The Pennsylvania State University. Additional experts in the areas of geology, geophysics, and underground engineering were appointed to the Ketch subcommittee.

Besides numerous contacts in Pennsylvania with officials of the AEC Plowshare Program, the Lawrence Radiation Laboratory, the Public Health Service, the AEC Nevada Operations Office, and the gas company, a group of representatives of the subcommittee and the various departments visited the

Nevada Test Site and the Nevada Operations Office to discuss the project in greater detail and to have some additional specific questions answered. At no time were we told that the information was not available.

We were also invited to the Gasbuggy symposium, and I received a personal invitation to work with the Public Health Service's environmental monitoring team during the briefing sessions and during the actual Gasbuggy detonation. There was no question that an effective rapport was being established between the Federal and State Governments to assure that joint decisions concerning the safety of the project could be made.

The "Ketch" subcommittee had, in the meantime, completed its work on reviewing the proposal. The report was accepted and forwarded to the Governor and the Departments concerned. The report and its recommendations are indeed the most significant single document from Pennsylvania on this project.

One of the problems arose from the method in which the "Project Ketch" proposal was submitted. The proposal was separated into five distinct phases as follows:

1. Site evaluation and confirmation
2. Execution
3. Chimney environment measurements
4. Storage facility development
5. Operation

The Phase I portion of the project included exploratory drilling, logging and pressure testing, safety surveys, permeability and high pressure tests, and some surface construction. The Advisory Committee concerned itself primarily with a technical review of Phase I only, since much of the information needed to verify the safety of the project could only be obtained during that phase. Its conclusions and recommendations can be summarized as follows:

> The committee believed that adequate details concerning the test work to be done during Phase I could be established by the AEC and the gas company as the Phase I portion proceeded. Therefore, the committee recommended that approval be given to proceed with this phase only provided:
>
> 1. That the phase would encompass all data and calculations necessary to confirm the site

acceptability and that certain questions raised in the complete report would receive adequate attention.

2. That an opportunity would be provided at the end of Phase I for an effective safety review by the AEC, utilizing the Panel of Safety Consultants, the Test Evaluation Panel, the Test Manager's Advisory Panel, and for Commonwealth representatives to review the findings before approval would be granted for Phase II.

3. That there would be assurance of appropriate compensation for any property damage or unlikely personal risks.

To quote directly from the report:

> "Commonwealth approval to proceed with Phase II and the subsequent phases of the project should be given after the Phase I evaluation, if it is found that a favorable decision by the AEC was based on an adequate and competent safety review to ascertain that the test would be accomplished without injury to people, either directly or indirectly, and without acceptable damage to the ecological system and natural and man-made structures."

Governor Shafer, in letters to Chairman Seaborg and the Columbia Gas Company, granted Commonwealth approval to proceed with the first phase of the project, listing the stipulations of the Advisory Committee's recommendations.

The project, as many of you know, is now in a state of limbo, or in one of the other states in proximity to Pennsylvania. Why was the project postponed?

One of the first recommendations made during discussions with the parties involved, was that an effective, large public information program be established jointly by the AEC, the Commonwealth, and the gas company. It was obvious that the reactions of individuals in the public would be similar to our first reaction. Pennsylvania has been one of the leaders in the atomic energy field. There are now 13 operating or planned power reactors in the state. There has been no adverse public response to these projects, mainly as a result of an effective long-term public relations program. Nuclear reactors are an accepted risk. However, nuclear explosives are not.

The response to our recommendation for a joint public information program went unheeded. Yes, public forums were held in the area; many man-miles were traveled by representatives of the Lawrence Radiation Laboratory, the AEC, the PHS, and the Columbia Gas Company to explain the project in detail to all interested groups. But once the adverse public reaction had begun, primarily out of fear, it was impossible to stop. Citizens groups were formed, signatures were obtained, and vocal critics of the project garnered much newspaper space.

The following slides, which were made from selected newspaper headlines, can tell the story much better than I can.

The title of this presentation is "The Role of a State Health Agency in an Underground Nuclear Experiment." Our role in this experiment ended rather abruptly, but it should have been two-fold--to protect the public health, naturally, but also to inform the public of that role and the steps we were taking to carry it out.

However, we, as a health agency, should not be placed in a position of promoting the project. This is the responsibility of those agencies and companies which are proposing it. I strongly urge that the experience in Pennsylvania not be quickly forgotten, but that an immediate effort be made by the Atomic Energy Commission to establish an effective Plowshare informational campaign. With proper direction, such a program could have stopped the groundswell before it became unmanageable, and would have allowed for a proper and unemotional evaluation of the safety of the project.

What did we all learn? A real lesson in the potent power of public opinion!

QUESTION FOR THOMAS M. GERUSKY

1. From P. R. Frederick:

   You have implied informed public opinion will support Plowshare projects. Do you have evidence of this? It seems unrealistic to me based upon Utah's attempted fluoridation of water supply experience! Very formidable and well-organized opposition developed.

   ANSWER:

   We have information that an uninformed public will react the opposite way. I think an informed public reacted the proper way in the reactor field. I think it can react properly in this field also.

STATE PARTNERSHIP IN ENVIRONMENTAL HEALTH AND SAFETY PHASE OF PLOWSHARE PROJECTS

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ABSTRACT

When experiments on projects involving Plowshare devices are conceived, the state chosen for the project should be invited to participate in planning the health and safety aspects and be prepared to actively participate in the D-Day phase as well as the post-detonation activity.

In California nuclear science technology and competence have preceded the social acceptance and use of nuclear devices for large scale Plowshare projects. However, the environmental surveillance program of the Bureau of Radiological Health in the State Department of Public Health has established an operative program which will be ready and able to function as an active participant or in a support role in environmental health phases of nuclear projects scheduled in the State.

A description of our present program will be included in this paper. This will enable the attendees and readers to realize capabilities which will be activated for participation and/or support roles during Plowshare activities in the State or in a neighboring state if the need arises.

* *

The people who planned this seminar prepared a logical outline for the entire program and then requested speakers to cover the respective subjects. The theme of this portion of the seminar was the "role of the state," with the previous speaker covering the underground engineering and this paper covering the role of the state in cratering. I was not familiar with the cratering experiments and consequently suggested an alternate title, which is a one sentence precis of this paper, namely, that the state in which the cratering experiment is being conducted should be an integral partner in the project, with the neighboring states being alerted, informed, and ready to exercise their role in case the scheduled project did not proceed as planned. In each state, the environmental health phase is naturally handled by its health department.

Background Information or How it was in California

On May 28, 1957, the AEC detonated the "Boltzman" nuclear device at 4:55 a.m., at the Nevada Test Site. About 6:00 p.m. the same day a portion of the cloud from this shot swung northwest across California through the area north of Lake Tahoe. It encountered localized thunderstorms and the resulting rainout gave measurable levels of radiation in scattered localities. Both the California Disaster Office and AEC monitoring teams checked these areas on May 28 and 29 and reported that the radiation levels found were not dangerous. However, in view of the State Health Department's responsibility for the health of the public in general and the safety of domestic water supplies in particular, a field survey to get firsthand detailed information was deemed desirable.

Since information regarding the exact path of the radioactive air mass was not available to the Department, the northeast quarter of the State lying north of U. S. Highway 40 and east of U. S. Highway 99 was selected for study. The plan followed was that most of the major highways were to be traversed with gamma survey instruments. Water, mud, and snow samples were to be taken where background radiation indicated fallout had occurred or where possible concentration of radioactivity could have occurred (i.e., water reservoirs, stock ponds, other water catchment areas).

Due to the magnitude of the task, assistance in monitoring and sample collection was requested from Butte, Plumas, and Shasta County Health Departments. Field monitoring instruments were furnished by the California Disaster Office. Radioanalyses of the samples were done by the Sanitation Laboratory using the California Disaster Office Radiological Laboratory truck which was assigned to the Division of Laboratories. The truck was moved to Quincy for this study. Seventy samples were collected for analysis and approximately 1,400 miles of highway were monitored with gamma survey meters.

Of the 70 samples only 3 (the snow samples at Donner Summit, Gold Lake and Lassen Summit) had significant radioactive content. None of these snow banks drained directly to domestic water reservoirs. Water from the reservoirs supplying the Quincy water system showed barely measurable amounts of radioactivity. These findings were not considered to be of public health significance due to the small size of the reservoirs (with a high flow-through rate) and the rapid decay characteristics of fallout radioactivity.

A report of these findings was included in the July report to the Governor's office. The comment that radioactivity in the three snow samples was above the limit considered "safe for continuous ingestion" received wide publicity and resulted in several follow-up inquiries from residents and recreational users of the Sierra Nevada area.

Because of the intense public interest, and in order to verify the earlier conclusions, a second survey was made August 7 through 9. Lassen Volcanic National Park, Lake Almanor, Quincy, Gold Lake, Beckworth, Donner Summit, and the highways between these areas were checked. Thirty samples were collected and approximately 600 miles of highway were monitored with gamma survey meters. No background radiation was found above normal nor were any of the water samples found to contain measurable amounts of radioactivity. The only snow sample obtainable was from a small residual snow bank in Lassen Park. The radioactivity found was about the same as that found on the first sampling.

These studies were executed under a 1955 law on radioactive wastes which states, "No person shall bury, throw away, or in any manner dispose of radioactive wastes in such a manner as to endanger the lives or health of human beings."

In the first calendar quarter of the following year the U.S.S.R. was conducting atmospheric tests of nuclear devices. On March 29, 1958, the California State Department of Agriculture collected some samples of leafy vegetables which were submitted to Dr. Hardin Jones, of the Donner Laboratory at the University of California, Berkeley, for radioassay. The radioactive content of twelve samples of eleven kinds of leafy vegetables collected from nine different localities in the North Coastal, San Joaquin and Sacramento Valleys of California ranged from 1970 to 41,800 disintegrations per minute for the unwashed vegetables. The radioactivity of the washed vegetables was much lower than that found on the unwashed samples. The radioactivity was characterized as mixed fission products.

In January 1959, a paper entitled, "An Analysis of the Public Health Implications of the Proposed Tracer Study of Ground Water Replenishment Operations in Los Angeles County" was submitted by the University of California, Berkeley, to the California State Department of Public Health. The introduction in this paper states, "The University of California, Berkeley, has presented a research proposal to the Los Angeles County Flood Control District concerned with the application of tritium to ground water tracing. The immediate objective of the study is to determine the water users benefiting from reclamation operations in the Upper Canyon Basin of the San Gabriel River. The long-range interest of the District is to confirm the extent to which the water reclamation program in the various basins of the San Gabriel River is effective in replenishing the ground water bodies of the Main Basin and within and downstream of the Montebello Forebay. The primary interest of the Sanitary Engineering Research Laboratory of the University is to establish the utility of tritium as a means of tracing underground waste travel. A further interest is the general phenomenon of hydraulic dispersion in flow through porous media."

The second paragraph of the Conclusions states, "The hazard of the investigation to the consumer in Los Angeles County has been demonstrated to be insignificant. The benefits of the investigation to the consumer are highly significant. A more economical development of the regional water resources will result in direct material benefits to all inhabitants. A better understanding of pollution movement in underground formations will be achieved with attendant improvements in water quality. The study is an opportunity for nuclear science to aid in solving a common problem in Southern California, that of a rapidly increasing demand for water and clearly limited water sources."

On January 23, 1959, the State Board of Public Health adopted a "Policy of California State Department of Public Health on Radioactive Tracer Studies," which contained six criteria. The proposed tritium tracer study met the six criteria but never materialized. It was rejected by adverse local public opinion.

California Environmental Surveillance Program - 1969

The essential features of this program are a radiochemical laboratory and a representative sampling network. The environmental media sampled are (1) Air, (2) Rain, Fallout, and Soil, (3) Domestic Water, (4) Sewage, (5) Milk, and (6) Diet. The samples are collected by 105 volunteer members of our local health departments. The location of the sampling stations and the number of stations for each of the six media sampled are shown in the following Figures 1 through 6. Table I is a summary of the environmental surveillance sampling and analyses.

These facilities and networks were tested and described in 1967 in an article by Amasa Cornish and George Uyesugi entitled, "Detection of Elevated Fallout Levels in California, January 1967." The abstract of the article which was published in Radiological Health Data and Reports, Vol. 9, Number 9, September 1968, is quoted:

> "California received a heavy fallout of radioactive debris beginning 4.5 days after a foreign nuclear device was detonated in the atmosphere on December 27, 1966. Highest air particulate levels occurred in Berkeley and Sacramento. Values obtained after allowing 3 days decay were 98 pCi/m^3 of air for both. Other air sampling stations had lesser amounts of fallout and Fresno received essentially no fallout. All milksheds in California were contaminated to some extent with radioactive iodine. Del Norte and Humboldt milk with 397 and 280 pCi/liter, respectively, contained the highest concentrations of iodine-131. These values were estimated to result in thyroid doses to children of 33 and 23 mrads, respectively. The apparent half-life for iodine-131 in the environment was calculated to


CALIFORNIA
AIR NETWORK
EUREKA
REDDING
CSSL
SANTA ROSA
SACRAMENTO
BERKELEY
SALINAS
FRESNO
BAKERSFIELD
BARSTOW
SAN BERNARDINO
LOS ANGELES
EL CENTRO
SAN DIEGO
14 STATIONS

FIGURE 1

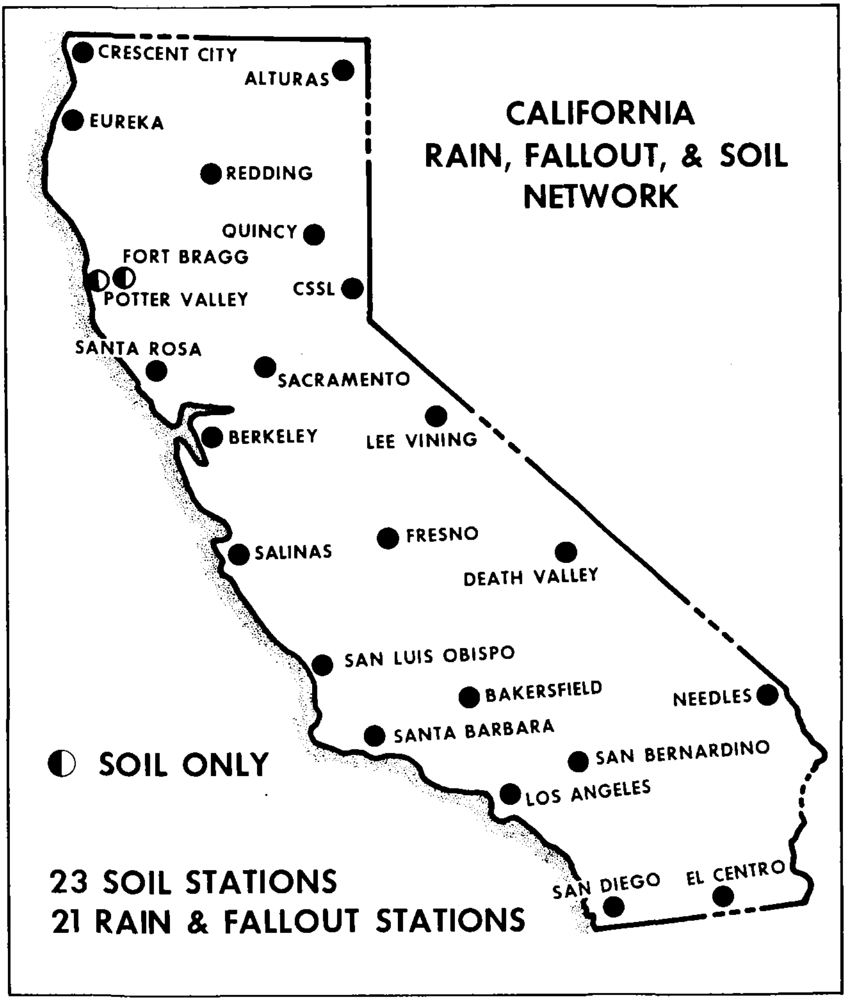
CALIFORNIA
RAIN, FALLOUT, & SOIL
NETWORK
CRESCENT CITY
ALTURAS
EUREKA
REDDING
QUINCY
FORT BRAGG
POTTER VALLEY
CSSL
SANTA ROSA
SACRAMENTO
BERKELEY
LEE VINING
SALINAS
FRESNO
DEATH VALLEY
SAN LUIS OBISPO
BAKERSFIELD
NEEDLES
SANTA BARBARA
SAN BERNARDINO
LOS ANGELES
SAN DIEGO
EL CENTRO
◐ SOIL ONLY
23 SOIL STATIONS
21 RAIN & FALLOUT STATIONS

FIGURE 2

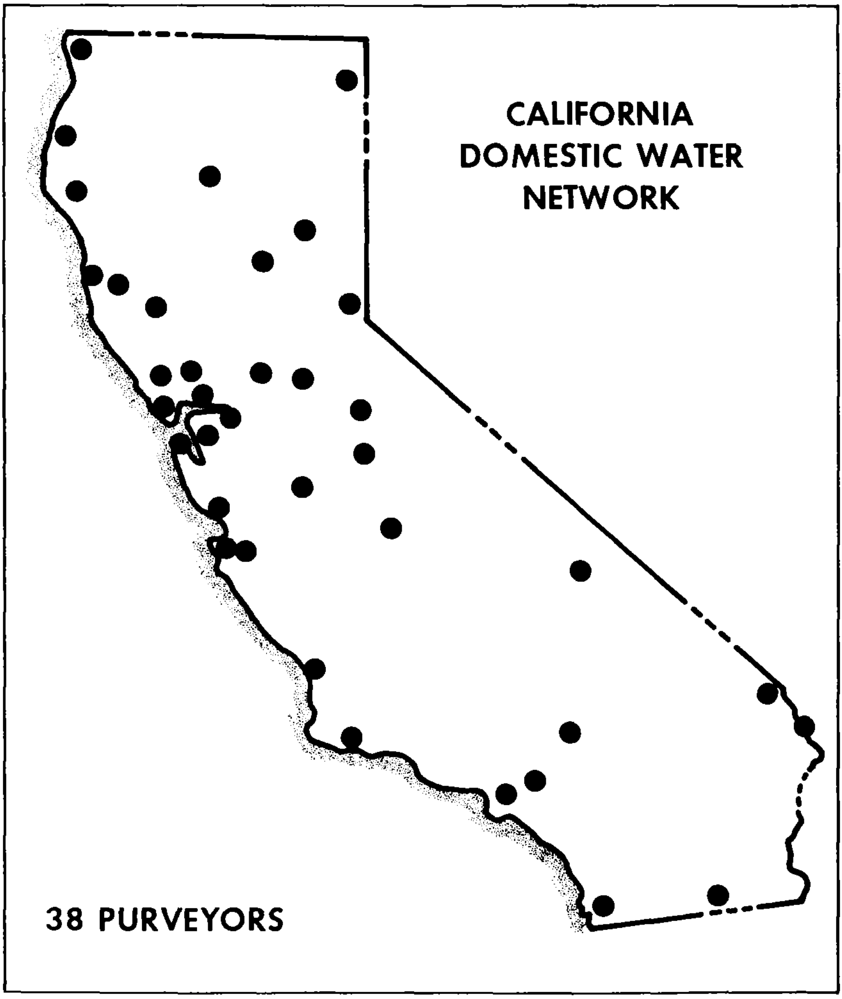

FIGURE 3


CALIFORNIA
SEWAGE NETWORK
EUREKA
VALLEJO
ANTIOCH
EAST BAY (MUD)
PLEASANTON
SAN FRANCISCO
LIVERMORE
SAN JOSE
SALINAS
FRESNO
BAKERSFIELD
SAN BERNARDINO
LOS ANGELES & L.A. COUNTY
ORANGE COUNTY
SAN DIEGO
EL CENTRO

FIGURE 4


CALIFORNIA
MILK NETWORK
DEL NORTE
HUMBOLDT
SHASTA
MENDOCINO
SONOMA
SACRAMENTO
SANTA CLARA
FRESNO
LOS ANGELES
SAN DIEGO
10 MILKSHEDS

FIGURE 5

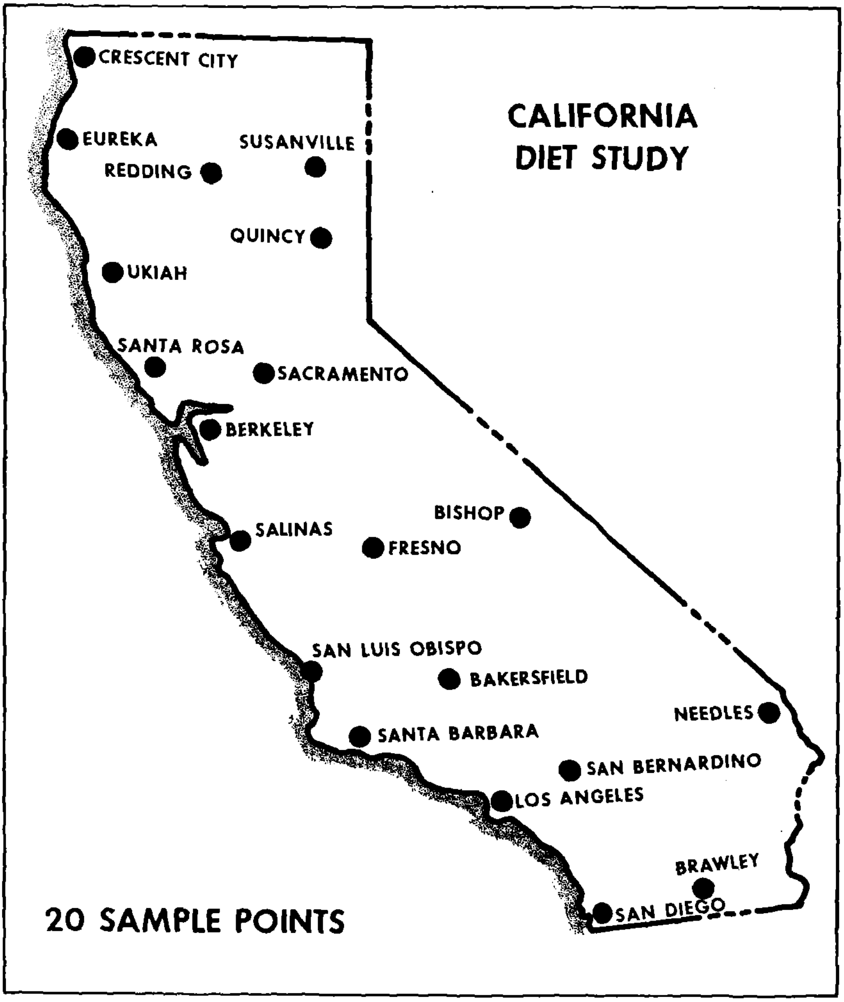
CALIFORNIA
DIET STUDY
CRESCENT CITY
EUREKA
SUSANVILLE
REDDING
QUINCY
UKIAH
SANTA ROSA
SACRAMENTO
BERKELEY
BISHOP
SALINAS
FRESNO
SAN LUIS OBISPO
BAKERSFIELD
NEEDLES
SANTA BARBARA
SAN BERNARDINO
LOS ANGELES
BRAWLEY
SAN DIEGO
20 SAMPLE POINTS

FIGURE 6

TABLE I

SUMMARY
ENVIRONMENTAL SURVEILLANCE
SAMPLING AND ANALYSES

Media Sampled	Sampling Stations	Sampling Frequency	Yearly Totals Samples	Yearly Totals Analyses
Air	14	Daily[3]	4,224	6,276
Fallout	21	Quarterly[2]	92	368
Water	50	Monthly	600	904
Sewage	20	Monthly	480	960
Milk	10	Monthly[4]	120	360
Diet	20	Quarterly[5]	80	520
Snow	12	5/Year	60	60
Specials	12	1/Year	240	480
			5,896	9,928

1. *Gamma scan for 8 isotopes reported as one (1) analysis above.*
2. 20 stations sampled quarterly; the Berkeley station is sampled monthly.
3. 10 stations sampled on work days only; 4 stations sampled every day.
4. Does not take into account increased sampling for continuing atmospheric nuclear tests.
5. From 1960-1964 the individual foods composing a diet were sampled. In 1964 the diet sampling replaced the food sampling.

be 3.2 days."

In addition to our radiological surveillance network, California has two other activities in its Bureau of Radiological Health, namely, (1) The X-Radiation Control Program which consists of Registration and Inspection of X-Ray Generators, the facilities in which they are operated, and educational assistance to the operators of this equipment; and (2) The Radioactive Material Control Program which includes Radium. This consists of a Licensing and Inspection group as required by AEC/States Agreement. However, California and several other states exercise control of Radium which has never been regulated by a Federal agency.

The State also has considerable manpower and equipment in the State Disaster Office, including (1) radiation measuring and calibration devices and facilities and (2) a statewide communication network tied in with the State Highway Patrol and the Police and Sheriff's Offices. Last year the State Department of Public Health and the State Disaster Office signed a memorandum of understanding for cooperative participation in handling emergency incidents involving radioactive materials. This cooperative activity includes the authority to impound or quarantine the radioactive material involved for the protection of the public. We have had two training courses recently on management of incidents involving radioactive material. These were sponsored by the State Health Department and the U. S. Public Health Service. In reviewing this information, it becomes obvious that the State has a rather complete radiation protection program.

Role of State Health Department in Plowshare Projects

With such equipment, facilities and competence available in a number of states--the Utah State program having been described in detail to you yesterday--the states are ready to assume the responsibility, in the Plowshare Program, granted them under the Federal Constitution, which is the protection of public health.

This role is beautifully described by Herman E. Hilleboe, M.D., DeLamar Professor of Public Health Practice, Columbia University, School of Public Health and Administrative Medicine, State of New York, in Chapter III, pages 23-31, of the Radiological Health Program Guide prepared by the Southern Interstate Nuclear Board for (and published by) the U. S. Department of Health, Education, and Welfare, Public Health Service, April 8, 1966. Page 29 of this reference shows the respective roles of the Public Health Service and State Health Agencies in Radiological Health, including the degrees of responsibility of each agency.

The legality of the responsibility of the state in protecting the public from radiation exposures was stated well by Mitchell Wendell, Ph.D., L.L.B, Counsel for the Council of State Governments, Washington, D. C., in Chapter II, Legal Aspects of Federal-State Relations in Radiation Protection, Radiological Health Program Guide referenced above.

The following is a quotation from pages 19 and 20 of this reference.

> "Federal-State relations in radiation protection from nuclear sources is a subject of peculiar import because of the unusual circumstances that attended the first harnessing of nuclear power, and because the revolutionary nature of this still new force inspires awe. Logically and practically it is clear that radiation protection from whatever source is merely a specialized phase of public health and safety regulation. Yet, the activities and responsibilities of the Atomic Energy Commission and of the military establishment undeniably give the Federal Government a special interest. So far the major direction of Federal and State action has been to clarify responsibilities and relationships as much as possible, and to fit the health and safety aspects or radiation protection into existing patterns of State and local administration and lawmaking as rapidly as practicable. Any other course would raise confusing questions of law and practical administration.
>
> "Conclusion. State activities in radiation protection, and more broadly in the entire field of radiological health as well, rest on several legal foundation stones. That the police power includes the power to protect the public health is both elementary and obvious; the conventional definition of the constitutional concept of police power is the power to regulate and protect 'health, safety, morals, and welfare.' Since this authority is left with the States by the Federal Constitution, its exercise is a legal attribute of all State governments. As already pointed out, some States have so far considered the police power to be sufficient basis for the assertion of jurisdiction to engage in any and all phases of radiation protection. An increasing number of States, either because they consider agreements with the AEC essential to their programs or because they look upon them as merely advantageous, are becoming agreement States. In these jurisdictions the police power is supplemented by the statutory assurance from Congress that no conflicting action of the Federal Legislature is likely to oust the legal authority of the State.
>
> "From the administrative point of view, the basis for State and local action also is clear. No matter how ingenious theorists become in building a separate category for nuclear activities, it remains true that State and local governments--not the Federal Government-inspect structures, issue and enforce sanitary codes, provide service and regulation in the field of industrial hygiene, fight fires, and patrol highways. Whenever the results of nuclear activity impinge on any of these areas, as they must constantly do, the State and local governments are the only ones in a position

> to act. They may do so with more or less skill, depending on their training and resources. They may do so more or less effectively, depending at least in part on the degree of specific authority to deal with nuclear-related matters conferred by State and local law. But they will act, or the public will be unnecessarily exposed to danger."

Earlier this month, 48 states were represented at the Conference of State Directors of Radiation and Safety Control Program. I do not have the permission to speak for this group. However, you have heard the remarks of the preceding speaker who is President of this organization, and you can see that he is inclined to support the State role as presented above. I hope the Conference of State and Territorial Officers will accept the report of this Conference of State Directors of Radiation and Safety, one part of which appears under the heading of Radiation Control Nationally and a sub-heading, "Ionizing Radiation--State Control," and reads, "The States are responsible for uncontrolled radiation sources in the environment as an unexpected result of a Plowshare project."

The respective states should have no fear of accepting the responsibility granted them under the Federal Constitution whether or not they have an AEC/State Agreement or whether they have a complete radiological health program. The State/Public Health Service relationship and support for this program is the same as it is for any other state program in protecting the health of the public. If the problem is too large to handle with the state resources, assistance will be furnished on request from the Public Health Service.

In regard to Plowshare in particular, each respective state would like to be a partner in this enterprise, with industry and the AEC being the other partners. We do not consider ourselves equal partners for all of the negotiations. However, after the detonation and particularly if it is in our State, the State may have a major role. In being a partner, we expect to be called into the planning meetings as early as possible, and I might say the earlier we are involved, the sooner will the project become a reality. The states should notify the PHS through its regional office and have this organization present at the first orientation meeting and most of the following meetings. After the first meeting, the State and PHS will prepare a draft of the cooperative plan to follow. This plan will be reviewed, modified, and updated frequently by both parties.

The success or failure of a proposed Plowshare project in any State will be determined by the public relations role executed by the State. This role will be more effectively executed if the State is informed early and can adequately and appropriately inform the local health authorities who will get the right story to the local press and residents as soon as possible. Yesterday Herb Parker stated he wasn't sure which radiation protection group the general public will trust. The local health group has been the protector for health and safety for so long the odds are in favor of their gaining the confidence of the local people and thereby effecting a good public relations program which will lend public support to the project, and as Abraham Lincoln said, "With public support you can do anything and without it you can do very little." This quotation is most applicable to Plowshare, and I repeat: If the AEC will include the States as a partner in the early talking and planning stage of Plowshare projects the chances of their becoming a reality are better than the odds in most of the activities in this city and the accomplishments will be realized much sooner.

I thank you for your devoted attention through the last phase of this seminar.

QUESTION FOR SIMON KINSMAN

1. From James Payne:

What analysis do you run on the sewage effluents and why?

ANSWER:

The California Radiological Monitoring Program includes the sampling of 20 sewage treatment plants throughout the state. Analyses of sewage samples, effluent and sludge, for alpha and beta activity provide a means of monitoring to insure that industrial radioactive wastes discharged into sewerage systems do not exceed prescribed limits. The surveillance of sewage assumes greater importance as isotope licensees become more numerous and as the quantity per user increases.

Water used by a city enters the city as domestic drinking water and leaves the city as sewage. If the city adds no radioactivity to the sewage, the radiological content of the domestic water and sewage should be the same. Therefore, interest centers around the difference in yearly averages between the radioactivity in the sewage effluent and the domestic water influent, and the ratio of sewage radioactivity to domestic water radioactivity. For example, two cities might have the following:

City	Water	Sewage	Difference	Ratio
A	10 pCi/l	15 pCi/l	5 pCi/l	1.5
B	10 pCi/l	80 pCi/l	70 pCi/l	8

Obviously, something is happening to city B that should be investigated while city A appears to be normal. In 1967 these ratios, in California cities that were sampled, ranged from 1.0 to 7.8 and the differences from 0.4 pCi/l to 37.4 pCi/l.

The present policy in California is that no city should discharge to the uncontrolled environment a sewage effluent containing more than 1×10^{-7} μCi/ml (100 pCi/liter) above the domestic water entering the city. In practice, the Bureau of Radiological Health of the California State Department of Public Health becomes concerned when the discharge values are one third of the maximum permissible value of 100 pCi/liter. An increase to this concentration indicates that some or several discharges are releasing too much radioactivity into the sewerage system. These discharges may be in excess of California's Radiation Control Regulations which are compatible with 10 CFR 20. A followup to determine the source of this increase in radioactivity enables us to determine licensee compliance or non-compliance with our regulations.

DISCUSSION OF HIGHLIGHTS AND CLOSING REMARKS

Dr. Raymond T. Moore
Acting Director, BRH
U. S. Public Health Service
Rockville, Maryland

Summarizing four full days and 38 pages of a technical symposium is an herculean task. It would be impossible, in the few minutes allowed me, to dwell adequately on each of the papers presented. Rather, I would like to review some reasons why we thought this symposium was both timely and necessary.

First and foremost in our mind was the need to emphasize the health and safety aspects. While our laboratory in Las Vegas and a few states have been deeply involved in Plowshare, the public health aspects were not widely known. Up to now there had been no forum where we and our colleagues could exchange ideas or views relating to the public health aspects of the Plowshare Program.

We considered it important to present the results and analyses of relevant studies of Plowshare activities conducted by various organizations. We believed it important to include discussions of air blast and ground motion effects as well as the transport of radioactivity for these are also of public health concern.

We attempted, and I believe succeeded, in bringing people of diverse interests and views together. In our opinion, it was necessary to bring into focus those problem areas where more research or information is needed.

Several of the speakers emphasized two major problems of concern. The more important of these is the need for declassification of certain Plowshare information. I believe you will be faced with resistance to the Plowshare Program from scientists and the general public as long as such data is kept under security wraps. People want to know the facts and be able to render their own judgment. Congressman Hosmer spoke of that in his excellent speech at the banquet Tuesday evening. He proposed that the AEC take steps to separate the Plowshare development activities from weapons development.

Dr. Carlyle Thompson indicated the other problem by noting the need of the states for public funds to monitor the environment after Plowshare events. Some way must be found to support state programs financially in order that they may gear up adequately to support industrial Plowshare projects.

I believe we have had a successful symposium. I am told the registration is in excess of 600. The success is due to you who have participated. Each session was fully attended. I have never been to a meeting where so many have stayed to the last as you have. Thank you.

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